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DESCHANEL'S
NATURAL PHILOSOPHY

BY PROFESSOR EVERETT.

PART III.
ELECTRICITY AND MAGNETISM.

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Chave vol. I, II.
Mar 29, 72

ELEMENTARY TREATISE

ON

NATURAL PHILOSOPHY.

BY

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INSPECTOR OF THE ACADEMY OF PARIS.

TRANSLATED AND EDITED, WITH EXTENSIVE ADDITIONS,

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IN FOUR PARTS.

PART III.

ELECTRICITY AND MAGNETISM.

ILLUSTRATED BY

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THE accurate method of treating electrical subjects which has been established in this country by Sir Wm. Thomson and his coadjutors, has not yet been adopted in France; and some of Faraday's electromagnetic work appears to be still very imperfectly appreciated by French writers. The Editor has accordingly found it necessary to recast a considerable portion of the present volume, besides introducing two new chapters (XXXIX^{A}. and XLI^{A}.) and an Appendix. Potential and lines of force are not so much as mentioned in the original.

The elements of the theory of magnetism have been based on Sir Wm. Thomson's papers in the *Philosophical Transactions;* and the description of the apparatus used in magnetic observatories has been drawn from the recently published work of the Astronomer Royal. The account of electrical units given in the Appendix is mainly founded on the Report of the Electrical Committee of the British Association for the year 1863.

M. Deschanel's descriptions of apparatus, of which some very elaborate examples occur in the present volume, left little to be desired in point of clearness. In no instance has it been found necessary to resort to the mere verbal rendering of unintelligible details.

ERRATUM.

In Fig. 356 the paper armatures are wrongly placed. Their broad parts should be exactly opposite the combs P P′, and their points *f f′* which project through the windows should be turned the opposite way to that represented in the figure, so that the revolving plate may pass them before it passes the combs.

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ELECTRICITY.

CHAPTER XXXV.

INTRODUCTORY PHENOMENA.

408. Fundamental Phenomena.—If a glass tube be rubbed with a silk handkerchief, both tube and rubber being very dry, the tube will be found to have acquired the property of attracting light bodies. If the part rubbed be held near to small scraps of paper, pieces of cut straw, sawdust, &c., these objects will move to the tube; sometimes they remain in contact [illegible], sometimes they are alternately attrac[illegible] [illegible]led, t[illegible] [illegible]s well as the duration of these [illegible] [illegible] of friction to which the tube [illegible]

[illegible] [illegible]esult is a sensation similar

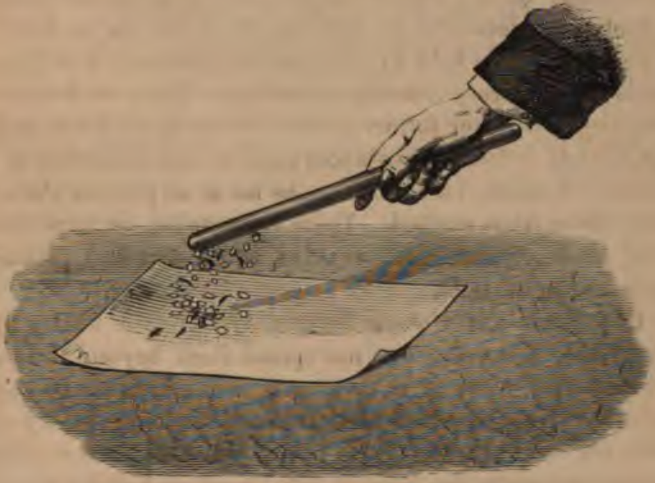

Fig. 332.—Attraction of Light Bodies by an Electrified Body.

to that produced by the contact of a cobweb. If the knuckle be held near the tube, a peculiar crackling noise is heard, and a bright *spark* passes between the tube and knuckle. The tube then has acquired peculiar properties by the application of friction. It is said to be *electrified*, and the name of *electricity* is given to the agent to which the various phenomena just described are attributed.

Glass is not the only substance which can be electrified by friction; the same property is possessed also by resin, sulphur, precious stones, amber, &c. The Greek name of this last substance (ἤλεκτρον) is the root from which the word *electricity* is derived.

At first sight it appears that this property of becoming electrified by friction is not common to all bodies; for if a bar of metal be held in the hand and rubbed with wool, it does not acquire the properties of an electrified body. But we should be wrong in concluding that metals cannot be electrified by friction; for if the bar be fitted on to a glass rod, and, while held by this handle, be struck with flannel or catskin, it may be very sensibly electrified. There is therefore no basis for the distinction formerly made between electrics and non-electrics, that is, between substances capable and incapable of being electrified by friction; for all bodies, as far as at present known, are capable of being thus excited. There is, however, an important difference of another kind between them, which was first pointed out by Stephen Grey in 1729.

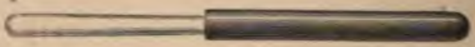

Fig. 333.—Electrification of a Metal by Friction.

409. Conductors and Non-conductors.—In certain bodies, such as glass and resin, electricity does not spread itself beyond the parts of the surface where it has been developed; while in other bodies, such as metals, the electricity developed at any point immediately spreads itself over the whole body. Thus, in the last-mentioned experiment, the signs of electricity are immediately manifested at the end of the metal bar which is farthest from the glass rod, if the end next the rod be submitted to friction. Bodies of the former kind, such as glass, resin, &c., are said to be *non-conductors.* Metals are said to be good *conductors.* A non-conductor is often called an *insulator*, and a conductor supported by a non-conductor is said to be *insulated.* The appropriateness of these expressions is evident. No substance is perfectly non-conducting, but the difference in co ing power between what are called non-conductors and good conductors, is enormous. The following are lists of conductors and non-conductors, arranged, at least approximately, in order of their conducting powers. In the list of conductors, the best conductors are put first; in the list of non-conductors, the worst conductors (or best insulators) are put first.

CONDUCTORS.

All metals.
Well-burned charcoal.
Plumbago.
Concentrated acids.
Dilute acids.
Saline solutions.
Metallic ores.
Animal fluids.
Sea water.
Spring water.
Rain water.
Snow.
Living vegetables.
Flax.
Hemp.
Living animals.
Flame.
Moist earth and stones.

NON-CONDUCTORS.

Shellac.
Amber.
Resins.
Sulphur.
Wax.
Jet.
Glass.
Mica.
Diamond.
Gems.
Ebonite.
Gutta-percha.
Silk.
Wool.
Feathers.
Dry paper.
Parchment.
Leather.
Baked wood.
Porcelain.
Marble.
Camphor.
Caoutchouc.
Chalk.
Lime.
Oils.
Metallic oxides.

The human body is a good conductor of electricity. If a person standing on a stool with glass legs be struck with a catskin, he becomes electrified in a very perceptible degree, and sparks may be drawn from any part of his body.

When an insulated and electrified conductor is allowed to touch another conductor insulated but not electrified, it is observed that, after the contact, both bodies possess electrical properties, electricity having been communicated to the second body at the expense of the first. If the second body be much the larger of the two, the electricity of the first is greatly diminished, and may become quite insensible. This explains the disappearance of electricity when a body is put in connection with the earth, which, together with most of the objects on its surface, may be regarded as constituting one enormous conductor. On account of its practically inexhaustible capacity for furnishing or absorbing electricity, the earth is often called *the common re*

It wi sily understood why it is not possible to electrify
ng it while it is held in the hand; since the

electricity, as fast as it is generated, passes off through the body into the earth.

Air, when thoroughly dry, is an excellent insulator; and electrified conductors exposed to it, and otherwise insulated, retain their charge with very little diminution for a considerable time. Dampness in the air is, however, a great obstacle to insulation, partly from the impaired insulating power of the air itself, and still more from the moisture which condenses on the insulating supports. Electrical experiments are accordingly very difficult to perform in damp weather. The difficulty is sometimes met by employing a stove to heat the air in the neighbourhood of the supports, and thus diminish its relative humidity. Sir W. Snow Harris employed heating-irons, which were heated in a fire, and then fixed near the insulating supports; and thus succeeded in exhibiting electrical experiments to an audience in the most unfavourable weather. Sir W. Thomson, by keeping the air in the interior of his electrometers dry by means of sulphuric acid, causes them to retain their charge with only a small percentage of loss in twenty-four hours. Dry frosty days are the best for electrical experiments, and next perhaps to these, is the season of dry cutting winds in spring.

410. Duality of Electricity.—The elementary phenomena which we have mentioned in the beginning of this chapter may be more accurately studied by means of the electric pendulum, which consists of a pith-ball suspended by a silk fibre from an insulated support. When an electrified glass rod is brought near the insulated ball, the latter is attracted; but as soon as it touches the glass tube, the attraction is changed to repulsion, which lasts as long as the ball retains the electricity which it has acquired by the contact. A similar experiment can be shown by employing, instead of the glass tube, any other body which has been electrified by friction, for example, a piece of resin which has been rubbed with flannel.

If, while the pendulum exhibits repulsion for the glass, the electrified resin is brought near, it is attracted by the latter; and conversely, when it is repelled by the resin, it is attracted by the glass. These phenomena clearly show that the electricity developed on the resin is not of the same kind as that developed on the glass. They exhibit opposite forces towards any third electrified body, each attracting what the other repels. They have accordingly received names which indicate opposition. The electricity which glass acquires when rubbed with silk, is called *positive;* and that which resin acquires by fr with flannel, *negative.* The former is also called *vitreous*, and the latter *resinous.* On repeating the experiment with other substances,

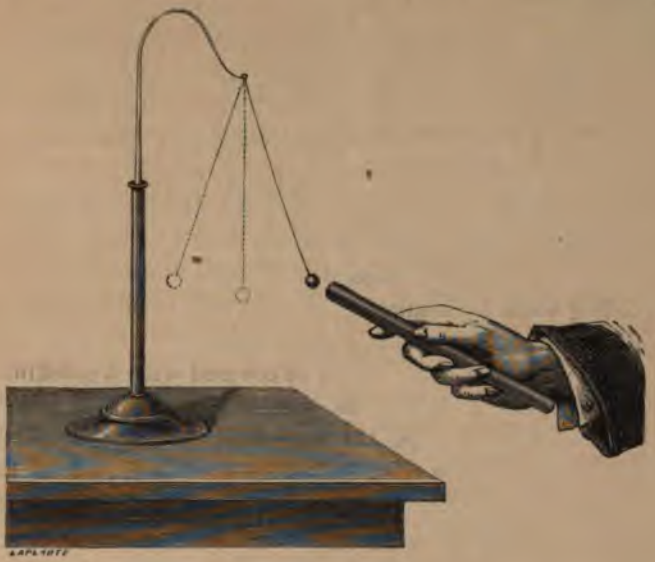

Fig. 334.—Electric Pendulum.

it is found that all electrified bodies behave either like the glass or like the resin.

410 A.—Without making any assumption as to what electricity is, we may speak of an electrified body as being *charged with electricity,* and we may compare quantities of electricity by means of the attractions and repulsions exerted. Bodies oppositely electrified must then be spoken of as charged with *electricities of opposite kind*, or *of opposite sign ;* and experiment shows that, whenever electricity of the one kind is developed, whether by friction or by any other means, electricity of the opposite sign is always developed in exactly equal quantity. If a conductor receives two charges of electricity of equal quantity but opposite sign, it is found to exhibit no traces of electricity whatever.

Electricities of like sign repel one another and those of unlike sign attract one another.—The magnitude of the force exerted upon each ot[illegible] two electrified bodies, is not altered in amount by [illegible] n of the electricity of one or both of them, provided [illegible] f electricity, and their distribution over the two bodies, remain unchanged. If the sign of one only be changed, the mutual force is simply reversed, and if the signs of both be changed, the force is not changed at all.

411.—The simultaneous development of both kinds of electricity is illustrated by the following experiment:—Two persons stand on stools with glass legs, and one of them strikes the other with a catskin. Both of them are now found to be electrified, the striker positively, and the person struck negatively, and from both of them sparks may be drawn by presenting the knuckle.

The kind of electricity which a body obtains by friction with another body, evidently depends on the nature of their surfaces. If, for example, we take two discs, one of glass, and the other of metal, and, holding them by insulating handles, rub them briskly together, we shall find that the metal becomes negatively, and the glass positively electrified; but if the metal be covered with a catskin, and the experiment repeated, it will be the glass which will this time be negatively electrified. In the subjoined list, the substances are arranged in such order that, generally speaking, each of them becomes positively electrified by friction with those which follow it, and negatively with those which precede it.

Fur of cat.
Polished glass.
Woollen stuffs.
Feathers.
Wood.
Paper.
Silk.
Shellac.
Rough glass.

411 A. Hypotheses regarding the Nature of Electricity.—Two theories regarding the nature of electricity must be described on account of the historical interest attaching to them.

The two-fluid theory, originally propounded by Dufaye, reduced to a more exact form by Symmer, and still very extensively adopted, maintains that the opposite kinds of electricity are two fluids. Positive electricity is called the *vitreous fluid*, and negative electricity the *resinous fluid*. Fluids of like name repel, and those of unlike name attract each other. The union of equal quantities of the two fluids constitutes the neutral fluid which is supposed to exist in very large quantity in all unelectrified bodies. When a body is electrified, it gains an additional quantity of the one fluid, and loses an equal quantity of the other, so that the total amount of electric fluid in a body is never changed; and (as a consequence of this last condition) when a current of either fluid traverses a body in any direction, an equal current of the other fluid traverses it in the opposite direction.

This theory is in complete agreement with all electrical phenomena so far as at present known; but as it is conceivable that the two electricities, instead of being two kinds of matter, may be two kinds of motion, or, in some other way, may be opposite states of one and the same substance, it is more philosophical to avoid the assumption involved in speaking of *two electric fluids*, and to speak rather of *two opposite electricities.* They may be distinguished indifferently by the names *vitreous* and *resinous*, or *positive* and *negative.*

The one-fluid theory, as originally propounded by Franklin, maintained the existence of only one electric fluid, which unelectrified bodies possess in a certain normal amount. A positively electrified body has more, and a negatively electrified body less than its normal amount. The particles of this fluid repel one another, and attract the particles of other kinds of matter, at all distances. Æpinus, in developing this theory more accurately, found it necessary to introduce the additional hypothesis that the particles of matter repel one another. Thus, according to Æpinus, the absence of sensible force between two bodies in the neutral condition, is due to the equilibrium of four forces, two of which are attractive, and the other two repulsive. Calling the two bodies A and B, the electricity which A possesses in normal amount, is repelled by the electricity of B, and attracted by the matter of B. The matter of A is attracted by the electricity of B, and repelled by the matter of B. These four forces are all equal, and destroy one another; but, without the supplementary hypothesis of Æpinus, one of the four forces is wanting, and the equilibrium is not easily explained. To reconcile Æpinus's addition with the Newtonian theory of gravitation, it is necessary to suppose that the equality between the four forces is not exact, the attractions being greater by an infinitesimal amount than the repulsions.

The one-fluid theory in this form is, like the two-fluid theory, consistent with the explanation of all known phenomena. But it is to be remarked that there is no sufficient reason, except established usage, for deciding which of the two opposite electricities should be regarded as corresponding to an excess of the electric fluid.

Franklin was the author of the terms positive and negative to denote the two opposite kinds of electrification; but the names can legitimately be retained without accepting the one-fluid theory, ding that opposite signs imply forces in opposite directions, connection between the *positive* sign and the forces *reous* electricity is merely conventional.

411 B.—In speaking of electric currents, the language of the one-fluid theory is almost invariably employed. Thus, if A is a conductor charged positively, and B a conductor charged negatively; when the two are put in connection by a wire, we say that the direction of the current is from A to B; whereas the language of the two-fluid theory would be, that a current of vitreous or positive electricity travels from A to B, and a current of resinous or negative from B to A.

CHAPTER XXXVI.

ELECTRICAL INDUCTION.

412. Induction.—In the preceding chapter we have spoken of movements of material bodies caused by electrical attractions and repulsions. We have now to treat of the movement of electricity itself in obedience to the attractions or repulsions exerted upon it by other electricity. This kind of action is called *induction.*

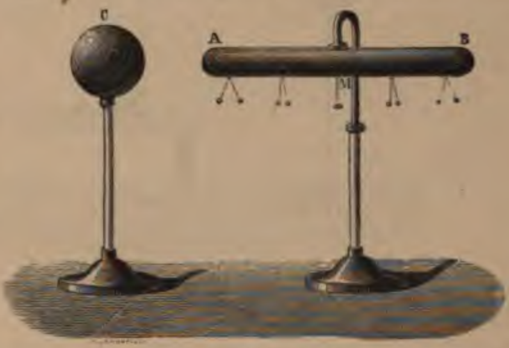

Fig. 336.—Electrification by Influence.

It may be illustrated by means of the arrangement shown in Fig. 336. The apparatus consists of a sphere C which is electrified positively, suppose, and of a conducting insulated cylinder A B placed near it. From this latter are suspended at equal distances a few pairs of pith-balls. When the cylinder is brought near the sphere, the balls are observed to diverge. The divergence of the different pairs is not the same, but goes on decreasing from the pair nearest the cylinder until a point M is reached, where there is no divergence. Beyond this the divergence goes on increasing. The neutral point M does not exactly [illegible] length of the cylinder, but is nearer the end [illegible] rmer end is found to be more strongly

[illegible] ends of the cylin[illegible] rged
[illegible] e end A being [illegible] and

the end B positively electrified. We have only to bring an electrified stick of resin near the pith-balls at A, when these will be found to be repelled; if, on the contrary, it be held near those at B, they will be attracted.

The explanation is, that the positive electricity with which C is charged attracts the negative electricity of AB to the end A, and repels the positive to the end B. This action is more powerful at A than at B, on account of the greater proximity of the influencing body, and for the same reason the effect falls off more rapidly in the portion AM than in MB.

If the cylinder be brought closer to the sphere, the divergence of the balls increases; if it be removed farther from it, the divergence diminishes. Finally, all signs of electricity disappear if the sphere be taken away, or connected with the earth.

If, while the cylinder is under the influence of the electricity of C, the end B is connected with the earth, the pith-balls at this end immediately collapse, while the divergence of those at A increases. The explanation is that the electricity which was repelled to the end B escapes to the earth, and thus affords an opportunity for a fresh exercise of induction on the part of the sphere, which increases the accumulation of negative electricity at A. We may also remark that the whole of the cylinder is now negatively electrified, the neutral line being pushed back to the earth. If the earth-connection be now broken, and the sphere C be then re [redacted]
remain negatively electrified, and will be
it had been touched by a negatively-ele

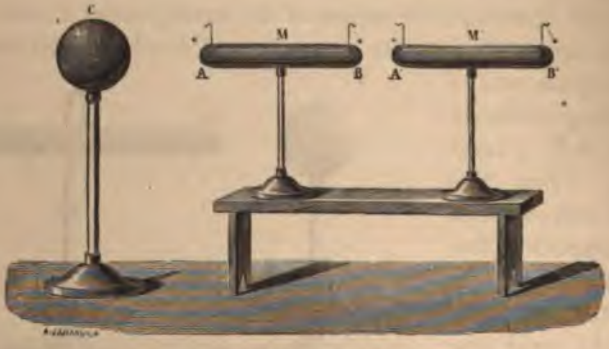

Fig. 337. -Successive Induction.

of giving a charge to a conductor is called *charging by induction*, and the charge thus given is always opposite to that of the *inducing body* C.

If a series of such conductors as AB be placed in line, without contact, and the positively-electrified body C be placed opposite to one end of the series, all the conductors will be affected in the same manner as the single conductor in the last experiment. They will all be charged with negative electricity at the end next C, and with positive electricity at the remote end, the effect, however, becoming feebler as we advance in the series. In this experiment each of the conductors acts inductively upon those next it; for example, if there be two conductors AB, A′B′, as in Fig. 337, the development of electricity at A′ and B′ is mainly due to the action of the positive electricity in MB. If the conductor AB be removed, the pith-balls at A′ and B′ will diminish their divergence.

The molecules of a body may be regarded as such a series of conductors, or rather as a number of such series. When an electrified body is brought near it, each molecule may thus become positive on one side and negative on the other. In the case of good conductors, this polarization is only instantaneous, being destroyed by the discharge of electricity from particle to particle. Good insulators are substances which are able to resist this tendency to discharge, and to maintain a high degree of polarization for a great length of time. This is Faraday's theory of "induction by contiguous particles."

413. Electrical Attraction and Repulsion.—The attraction which is observed when an electrified is brought near to an unelectrified body, is dependent upon induction. Suppose, for instance, that a body C, which is positively electrified, is brought near to an insulated and uncharged pith-ball. Negative electricity is induced on the near side of the pith-ball, and an equal quantity of positive on the further side. The former, being nearer to the body C, is more strongly attracted than the other is repelled. The ball is therefore upon the whole attracted.

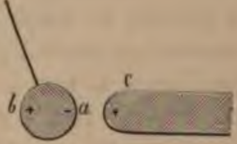

Fig. 338.—Electrical Attraction.

If the pith-ball, instead of being insulated, is suspended by a con-
thread from a support connected with the earth, it will be
attracted than before, as it is now entirely charged
tricity.

insulated conductor, the algebraic sum of the electricities induced upon it by the presence of a neighbouring electrified body must be zero. If the pith-ball be insulated, and have an independent charge of either kind of electricity, the total force exerted on the pith-ball is the algebraic sum[1] of the two following quantities:—

(1) The force which the ball would experience, if it had no independent charge. This force, as we have just seen, is always attractive.

(2) The force due to the independent charge when distributed over the ball as it would be if C were removed. This second force is attractive or repulsive, according as the independent charge is of unlike or like sign to that of C. In the latter case, repulsion will generally be observed at distances exceeding a certain limit and attraction at nearer distances, the reason being that the force (1) due to the induced distribution increases more rapidly than the other as the distance is diminished.

It is important to remember this in testing, by the electric pendulum, or by any other electroscope, the kind of electricity with which a body is charged. In bringing the body towards the electroscope, the first movement produced is that which is to be observed, and repulsion is in general a more reliable test of kind of electricity than attraction.

415. Electroscopes.—An electroscope is an apparatus for detecting the presence of electricity, and determining its sign. The insulated electric pendulum is an electroscope. If the pith-ball, when itself uncharged, is attracted by a body brought near it, we know that the body is electrified. To determine the kind of electricity, the body is allowed to touch the pith-ball, which is then repelled. At this moment an excited glass tube is brought near. If it repels the ball, this latter, as well as the body which touched it, must be electrified positively. If the glass tube attracts it, or, still more decisively, if excited resin or sealing-wax repels it, the ball and the body which touched it are electrified negatively. The loss of electricity from the pith-ball is often so rapid as to render this test of sign somewhat uncertain.

The *gold-leaf electroscope* (Fig. 339) is const[illegible] follows:—

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[1] We here suppose C to be a non-conductor, so that the di[illegible]tricit[illegible] not affected by the presence of the pith-ball. If C be a cond[illegible] upon it will be to favour attraction, so that an attractive forc[illegible] forces specified in the text.

Two small gold-leaves are attached to the lower end of a metallic rod, which passes through an opening in the top of a bell-glass, and terminates in a ball. The metallic rod is sometimes, for the sake of better insulation, inclosed in a glass tube secured by sealing-wax or some other non-conducting cement, and, for the same purpose, the upper part of the bell-glass is often varnished with shellac, which is less apt than glass to acquire a deposit of moisture from the air. The bell-glass is attached below to a metallic base, which excludes the external air. For the gold-leaves are sometimes substituted two straws, or two pith-balls suspended by linen threads; we have thus the *straw-electroscope* and the *pith-ball electroscope.*

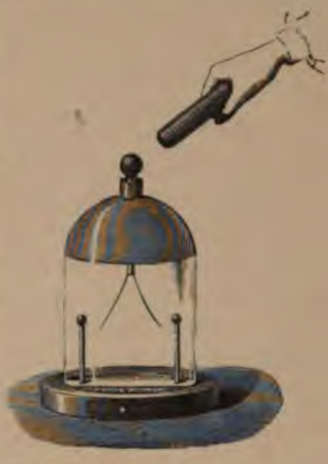
Fig. 339.—Gold-leaf Electroscope.

To test whether a body is electrified, it is brought near the ball at the top of the electroscope. The like electricity is repelled into the leaves, and makes them diverge, while the unlike is attracted into the ball. The sign of the body's charge may be determined in the following manner:—While the leaves are divergent under the influence of the body, the operator touches the ball with his finger. This causes the leaves to collapse, and gives to the insulated conductor composed of leaves, rod, and ball, a charge opposite to that of the influencing body. The finger must be removed while the influencing body remains in position, as the amount of the induced charge depends upon the position of the influencing body at the instant of breaking connection. On now withdrawing the influencing body, the charge of unlike electricity is no longer attracted to the ball, but spreads over the whole of the conductor, and causes the leaves to diverge. If, while this divergence continues, an excited glass tube, when gradually brought towards the ball, diminishes the divergence, we know that the body in ques[illegible]s electrified positively. If it increases the divergence, the [illegible] electrified nega-

[illegible] n bringi[illegible] bodies near the [illegible] es are [illegible] be ruptured by quick movements. If they diverge so widely as to touch the sides of the bell-glass, it is often difficult to detach them from the glass without tearing. To prevent this contact, two metallic columns are interposed, communicating with the ground. If the leaves diverge too widely, they touch these columns and lose their electricity.

CHAPTER XXXVII.

MEASUREMENT OF ELECTRICAL FORCES.

416. Coulomb's Torsion-balance.—Coulomb, who was the first to make electricity an accurate science, employed in his researches an instrument which is often called after his name, and which is still extensively employed. It depends on the principle that the torsion of a wire is simply proportional to the twisting couple. We shall first describe it, and then point out some of its applications.

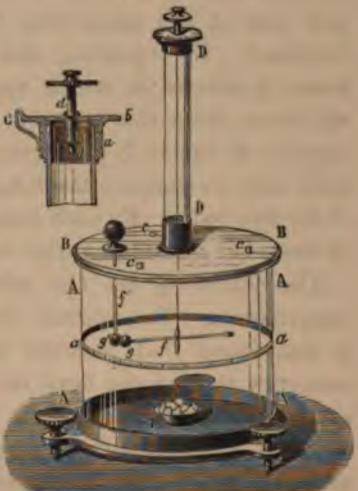

Fig. 340.—Coulomb's Torsion-balance.

It consists of a cylindrical glass case A A (Fig. 340), from the upper end B of which rises another glass cylinder D D of much smaller diameter. This small cylinder is fitted at the top with a brass cap *a*, carrying an index C. Outside of this, and capable of turning round it, is another cap *b*, the top of which is divided into 360 equal parts. In the centre of the cap *b* is an opening through which passes a small metal cylinder *d*, capable of turning in the opening with moderate friction, and having at its lower end a notch or slit. When the cap *b* is turned, the cylinder *d* turns with it; but the latter can also be turned separat[illegible] as not to change the reading. These parts com[illegible] the *tor*[illegible] very fine metallic wire is held by the notch, [illegible] of metal, through which pass[illegible] light [illegible] end a small gilt ball *g*. [illegible]cular scale runs round the outside of the large cylinder in the plane of the needle. Finally, opposite the zero of this scale, there is a fixed ball *g* of some conducting material, supported by a rod *f* of shellac, which passes through a hole in the cover of the cylindrical case.

417. Laws of Electric Repulsion.—To illustrate the mode of employing this apparatus for electrical measurements, we shall explain the course followed by Coulomb in investigating the law according to which electrical repulsions and attractions vary with the distance. The index is set to the zero of the scale. The inner cylinder *d* is then turned, until the movable ball just touches the fixed ball without any torsion of the wire. The fixed ball is then taken out, placed in communication with an electrified body, and replaced in the apparatus. The electricity with which it is charged is communicated to the movable ball, and causes the repulsion of this latter through a number of degrees indicated by the scale which surrounds the case. In this position the force of repulsion is in equilibrium with the force of torsion tending to bring back the ball to its original position. The graduated cap *b* is then turned so as to oppose the repulsion. The movable ball is thus brought nearer to the fixed ball, and at the same time the amount of torsion in the wire is increased. By repeating this process, we obtain a number of different positions in which repulsion is balanced by torsion. But we know, from the laws of elasticity, that the force (strictly the couple[1]) of torsion is proportional to the angle of torsion. Hence we have only to compare the total amounts of torsion with the distances of the two balls. By such comparisons Coulomb found that the force of electrical repulsion varies *inversely as the square of the distance.*

The following are the actual numbers obtained in one of the experiments. The original deviation of the movable ball being 36°, it was found that, in order to reduce this distance to 18°, it was necessary to turn the head through 126°, and, for a farther reduction of the deviation to 8°·5, an additional rotation through 441° was required. It will thus be perceived that at the distances of 36°, 18°, and 8°·5, which may be practically considered as in the ratio of 1, $\frac{1}{2}$, and $\frac{1}{4}$, the forces of repulsion were equilibrated by torsions of 36°,

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[1] The repulsive force on the movable ball is equivalent to an equal and parallel
acting at the centre of the needle (the point of attachment of the wire).
arm is the perpendicular from this centre on the line joining the ba
be equal to the couple of torsion. The other component produces
suspending wire from the vertical.

126° + 18° = 144°, and 441 + 126 + 8·5 = 575°·5 respectively. Now 144 is 36 × 4, and 575·5 may be considered as 576, or 36 × 16. Hence we perceive that, as the distance is divided by 2, or by 4, the force of repulsion is multiplied by 4 or by 16, which precisely agrees with the law enunciated above.

418. Equation of Equilibrium.—We must, however, observe that in this mode of reducing the observations two inaccurate assumptions are made. First, the distance between the balls is regarded as being equal to the arc which lies between them, whereas it is really the chord of that arc. Secondly, the force of repulsion is regarded as acting always at the same arm, whereas its arm, being the perpendicular from the centre on the chord, diminishes as the distance increases. The following investigation is more rigorous.

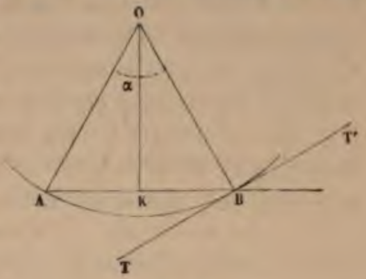

Fig. 341.

Let A O B (Fig. 341), the angular distance of the balls, be denoted by α, and let l be the length of the radius O A. Then the chord A B is $2l \sin \frac{1}{2} \alpha$, and the arm O K is $l \cos \frac{1}{2} \alpha$. Let f denote the force of repulsion at unit distance, and n the couple of torsion for 1°. Then the force of repulsion in the given position is $\frac{f}{4l^2 \sin^2 \frac{1}{2}\alpha}$ if the law of inverse squares be true, and the moment of this about the centre is $\frac{f \cos \frac{1}{2}\alpha}{4l \sin^2 \frac{1}{2}\alpha}$, which must be equal to nA, if A be the number of degrees of torsion. Hence we have

$$\frac{f}{4nl} = \mathrm{A} \sin \tfrac{1}{2} \alpha \tan \tfrac{1}{2} \alpha,$$

and as the first member of this equation is constant, the second member must be constant also for different values of A and α, if the law of inverse squares be true. The degree of constancy is shown by the following table:—

	α	A	A $\sin \frac{1}{2}\alpha \tan \frac{1}{2}\alpha$
1st experiment, ...	36	36	3·614
2d experiment, ...	18	144	3·568
3d experiment, ...	8·5	575·5	3·169
Supposed case, ...	9	576	3·557

The difference between the first and second numbers of the last column is insignificant. That between the second and third is more considerable,[1] but in reality only corresponds to an error of half a degree in the measurement of the arc.

419. Case of Attraction.—The law of attractions may be investigated by a similar method. The index is set to zero, and the central piece is turned so as to place the movable ball at a known distance from the fixed ball. The two balls are then charged with electricity of different kinds. The movable ball is accordingly attracted towards the other, and settles in a position in which attraction is balanced by torsion. By altering the amount of torsion, different positions of the ball can be obtained. On comparing the distances with the corresponding torsions, it is found that the same law holds as in the case of repulsion. The experiment, however, is difficult, and is only possible when the balls are very feebly electrified. To prevent the contact of the two balls, Coulomb fixed a silk thread in the instrument, so as to stop the course of the movable ball.

420. Law of Attraction and Repulsion as depending on Amount of Charge.—We may assume as evident, that when an electrified ball is placed in contact with a precisely equal and similar ball, the charge will be divided equally between them, so that the first will retain only half the charge which it had before contact.

Suppose that an observation on repulsion has just been made with the torsion-balance, and that we touch the fixed ball with another exactly equal insulated ball, which we then remove. It will be found that the amount of torsion requisite for keeping the movable ball in its observed position is just half what it was before. The same result will be obtained by touching the movable ball with a ball of its own size. We conclude that, if the charge of either body be altered, the attractive or repulsive force between the bodies at given distance will be altered in the same ratio. The law is not rigorously true for bodies of finite size, unless the distribution of the electricity on the two bodies remains unchanged. When the two bodies are very small in all their dimensions in comparison with the distance between them, their mutual force is represented by the expression

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[1] We have already seen that the mutual induction of two conductors tends to diminish their mutual repulsion, and that this inductive action becomes more important as the distance is diminished. Hence the repulsion at distance 9 should be less than a quarter of that at distance 18. The apparent error thus confirms the law.

Many persons have adduced, as tending to overthrow Coulomb's law of inverse squares, experimental results which really confirm it. Except when the dimensions of the charged bodies are very small in comparison with the distance, the observed attraction or repulsion is the resultant of an infinite number of forces acting along lines drawn from the different points of the one body to the different points of the other. The law of inverse squares applies directly to these several components, and not to the resultant which they yield. The latter can only be computed by elaborate mathematical processes.

It is incorrectly assumed in the text that the law ought to apply [illegible] two spheres, when by their distance we understand the distance between their [illegible] it is obvious that the distance of the nearest points should give a bette[illegible] between the centres.

The strongest evidence for the rigorous exactness of the law of in[illegible] see § 421 c.

$$\frac{q\,q'}{\mathrm{D}^2},$$

q and q' denoting their charges, and D the distance. If this expression has the positive sign, the force is repulsive, if negative, attractive.

421. Electricity resides on the Surface.—Electricity (subject to the

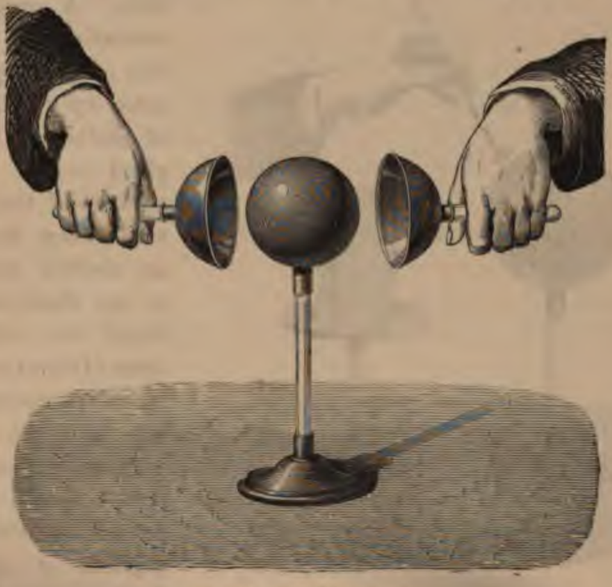

Fig. 342.—Biot's Experiment.

exceptions mentioned below) resides exclusiv[illegible] the external surface of a conductor. This is perhaps implie[illegible] experimental fact [illegible] ed by Coulomb, that whe[illegible] and a hollow [illegible] iameter are allowed [illegible] h each other, [illegible] is divided equall[illegible] en them. A direct demonstration is afforded by the following experiment of Biot:—

We take an insulated sphere of metal, charge it with electricity, and cover it with two hemispheres furnished with insulating handles, which fit the sphere exactly (Fig. 342). If the two hemispheres be quickly removed, and presented to an electric pendulum, they will be found to be electrified, while the sphere itself will show hardly any traces of electricity. We must, however, remark that this experiment is rarely successful, and that generally the sphere remains very sensibly electrified. The reason of this is, that it is very difficult to remove the hemispheres so steadily, as not to permit their edges to touch the sphere after the first separation.

The following is a much surer form of the experiment:—

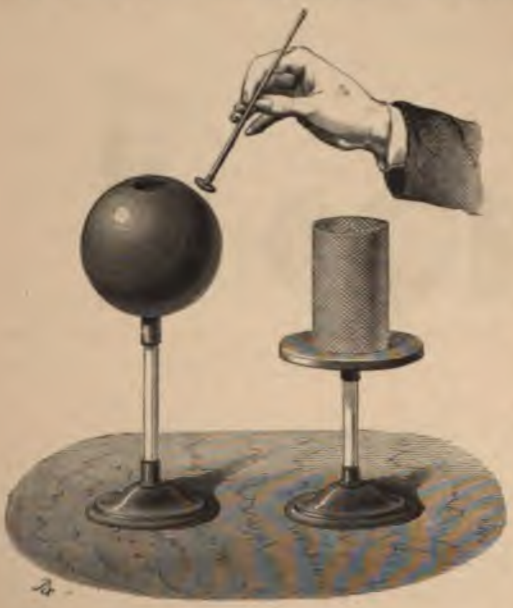

Fig. 343.—Proof-plane and Hollow Sphere.

A hollow insulated sphere, with an orifice in the top, is charged with electricity (Fig. 343). A *proof-plane*, consisting of a small disc of gilt paper insulated by a thin handle of shellac, is then applied to the interior surface of the sphere, and, when tested by an electric pendulum or an electroscope, is found to exhibit no trace of electricity. But if, on the contrary, the disc be applied to the external surface of the sphere, it will be found to be electrified, and capable of attracting light bodies. Faraday varied this experiment, by substituting a cylinder of wire-gauze for the sphere. This cylinder rested on an insulated disc of metal. The disc wa [illegible] electricity, and it was found that no trace of the elec [illegible] detected by applying the proof-plane to the interio [illegible] cylinder.

The following experiment is also due to Faraday. A metal ring is fixed upon an insulating stand (Fig. 344). To this ring is attached a cone-shaped bag of fine linen, which is a conductor of electricity. A silk thread, attached to the apex of the cone, and extending both ways, enables the operator to turn the bag inside out as often as required, without discharging it. When the bag is electrified, the application of the proof-plane always shows that there is electricity on the outer, but not on the inner surface. When the bag is turned inside out, the electricity therefore passes from one surface of the linen to the other.

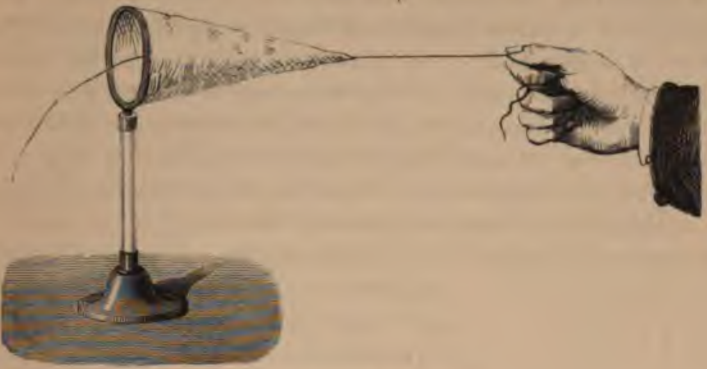

Fig. 344.—Faraday's Experiment.

421 A. Limitations of the Rule.—There are two exceptions to the rule that electricity is confined to the external surface of a conductor.

1. It does not hold for electric currents. We shall see hereafter in connection with galvanic electricity, that the resistance which a wire of given length opposes to the passage of electricity through it, depends not upon its circumference but upon its sectional area. A hollow wire will not conduct electricity so well as a solid wire of the same external diameter.

2. Electricity may be induced on the inner surface of a hollow conductor by the presence of an electrified body insulated from the conductor itself. If an insulated body charged with electricity be introduced into the interior of a hollow conductor, so as to be completely surrounded by it, but still insulated from it, it induces upon the inner surface a quantity equal to its own charge, but of opposite sign. If the conductor is insulated, an equal quantity, but of the same sign as the charge of the inclosed body, is repelled to the outside, and

this is true whether the conductor has an independent charge of its own or not. In this case, then, we have electricity residing on both the external and the internal surfaces of a hollow conductor, but it still resides only on the surfaces.

If a conducting body connected with the earth be introduced into the interior of a hollow charged conductor, so as to be partially surrounded by it, the body thus introduced will acquire an opposite charge by induction, and, by the reciprocal action of this charge, electricity will be induced on the inner at the expense of the outer surface of the hollow conductor, just as in the preceding case.

421 B. Ice-pail Experiment.—The effect of introducing a charged body within a hollow conductor is well illustrated by the following experiments of Faraday. Let A (Fig. 344 A) represent an insulated pewter ice-pail, ten and a half inches high and seven inches in diameter, connected by a wire with a delicate gold leaf electroscope E, and let C be a round brass ball insulated by a dry thread of white silk, three or four feet in length, so as to remove the influence of the hand holding it from the ice-pail below. Let A be perfectly discharged, and let C, after being charged at a distance, be introduced into A as in the figure. If C be positive, E also will diverge positively; if C be taken away, E will collapse perfectly, the apparatus being in good order. As C enters the vessel A, the divergence of E will increase until C is about three inches below the edge of the vessel, and will remain quite steady and unchanged for any greater depression. If C be made to touch the bottom of A, all its charge is communicated to A, and C, upon being withdrawn and examined, is found perfectly discharged. Now Faraday found that at the moment of contact of C with the bottom of A, not the slightest change took place in the divergence of the gold-leaves. Hence the charge previously d[illegible] tion on the outside of A must have been pr[illegible] acquired by the contact, that is, must hav[illegible] charge of C.

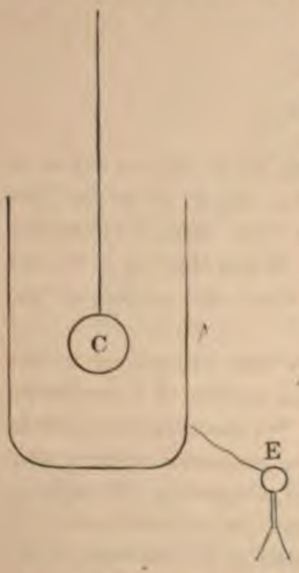

Fig. 344A.—Ice-pail Experiment.

He then employed four ice-pails (Fig. 344 B), arranged one within the other, the smallest innermost, insulated from each other by plates of shellac at the bottom, the outermost pail being connected with the electroscope. When the charged carrier-ball C was introduced within the innermost pail, and lowered until it touched the bottom, the electrometer gave precisely the same indications as when the outermost pail was employed alone. When the innermost was lifted out by a silk thread after being touched by C, the gold-leaves collapsed perfectly. When it was introduced again, they opened out to the same extent as before. When 4 and 3 were connected by a wire let down between them by a silk thread, the leaves remained unchanged, and so they still remained when 3 and 2 were connected, and finally when all four pails were connected.

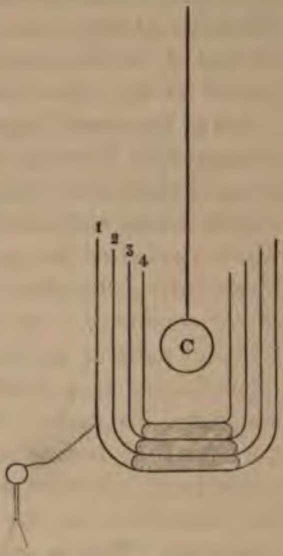

Fig. 344 B.—Experiment with Four Ice-pails.

421c. No Force within a Conductor.—When a hollow conductor is electrified, however strongly, no effect is produced upon pith-balls, gold-leaves, or any other electroscopic apparatus in the interior, whether connected with the hollow conductor, or insulated from it, provided, in the latter case, that they have no communication with bodies external to the hollow conductor. Faraday constructed a cubical box, measuring 12 feet each way, covered externally with copper wire and tin-foil, and insulated from the earth. He charged this box very strongly by outside communication with a powerful electrical machine; but a gold-leaf electrometer within showed no effect. He says, "I went into the cube and lived in it, using lighted candles, electrometers, and all other tests of electrical states. I could not find the least influence upon them, or indication of anything particular given by them, though all the time the outside of the cube was powerfully charged, and large sparks and brushes were darting off from every part of its outer surface."

[illegible] only on the external surface of a [illegible] at there is no electrical force in [illegible] ds a rigorous proof of the law of inverse squares. For if the conductor be a sphere removed from the influence of external bodies, its charge must be distributed uniformly over its surface. Now it admits of proof, and is well known to mathematicians, that a uniform spherical shell exerts no attraction at any point of the interior space, if the law of attraction be that of inverse squares, and that the internal attraction does not vanish for any other law.

421 D. Electrical Density and Distribution.—When the proof-plane is applied to different parts of the surface of a conductor, the quantities of electricity which it carries off are not usually equal. But the electricity carried off by the proof-plane is simply the electricity which resided on the part of the surface covered by it, for the proof-plane during the time of its contact is virtually part of the surface of the conductor. We must therefore conclude that equal areas on different parts of the surface of a conductor have not equal amounts of electricity upon them. It is also found that if the charge of the conductor be varied, the electricity resident upon any specified portion of the surface is changed in the same ratio. The ratio of the quantities of electricity on two specified portions of the surface is in fact independent of the charge, and depends only on the form of the conductor. This is expressed by saying that *distribution* is independent of charge, and that the distribution of electricity on the surface of a conductor depends on its form.

By the *average electrical density* on the whole or any specified portion of the surface of a conductor, is meant the quantity of electricity upon it, divided by its area. By the *electrical density at a specified point* on the surface of a conductor, is meant the average electrical density on an exceedingly small area surrounding it, in other words, the *quantity of electricity per unit area* at the point. The name is appropriate, from the analogy of ordinary material density, which is mass per unit volume, and is not intended to imply any hypothesis as to the nature of electricity. The name was introduced by Coulomb, who first investigated the subject in question, and is generally employed by the best electricians in this country. The term *thickness of electrical stratum*, which was introduced by Poisson, is much used in France, but is more open to objection from the coarse assumptions which it seems to involve.

The following are some of Coulomb's results. The dotted li
each of the figures is intended to represent, by its distanc
outline of the conductor, the electric density at eac

latter. In all cases it is to be understood that the conductor is so far removed from external bodies as not to be influenced by them:—

1. *Sphere* (Fig. 345). The electric density is the same for all points on the surface of a spherical conductor.

2. *Ellipsoid* (Fig. 346). The density is greatest at the ends of the longest, and least at the ends of the shortest axis; and the densities at these points are simply proportional to the axes themselves.[1]

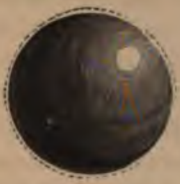

Fig. 345.—Distribution on Sphere.

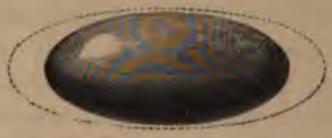

Fig. 346.—Distribution on Ellipsoid.

3. *Flat Disc* (Fig. 347). The density is almost inappreciable over the whole of both faces, except close to the edges, where it increases almost *per saltum*.

4. *Cylinder with Hemispherical Ends* (Fig. 348). The density is a minimum, and nearly uniform, at parts remote from the ends, and attains a maximum at the ends. The ratio of the density at the ends to that at the sides increases as the radius of the cylinder diminishes, the length of the cylinder remaining the same.

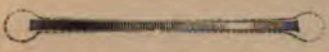

Fig. 347.—Distribution on Disc.

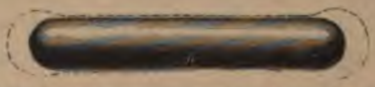

Fig. 348.—Distribution on Cylinder with rounded ends.

5. *Spheres in Contact.*—In the case of equal spheres, the charge, which is nothing at the point of contact, and very feeble up to 30° from that point, increases very rapidly from 30° to 60°, less rapidly from 60° to 90°, and almost insensibly from 90° to 180°. When the spheres are of unequal size, the charge at any point on the smaller

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[1] More generally, the density at any point on the surface of an ellipsoid is proportional to the length of a perpendicular from the centre of the ellipsoid on a tangent plane at the point.

If an ellipsoid, similar and nearly equal to the given one, be placed so that the corre- [illegible] of the two are coincident, we shall have a thin ellipsoidal shell, whose thick- [illegible] represents the electric density at that point.

[illegible] ogeneous matter attracting inversely as the square of the [illegible] ints in its interior.

sphere is greater than at the corresponding point on the larger one; and as the smaller sphere is continually diminished, the other remaining the same, the ratio of the densities at the extremities of the line of centres tends to become 2 : 1.

422. Method of Experiment.—The preceding results were obtained by Coulomb in the following manner. He touched the electrified body at a known point with the proof-plane, and then put the plane in the place of the fixed ball of the torsion-balance, the movable ball having previously been charged with electricity of the same sign. Repulsion was thus produced, and the amount of torsion necessary to keep the balls at a certain distance asunder was observed. He then repeated the experiment with electricity taken from a different point of the body under examination, and the ratio of the densities at the two points was given by the ratio of the torsions necessary to keep the balls at the same distance.

By way of checking the accuracy of this mode of experimentation, Coulomb electrified an insulated sphere, and measured the electric density on its surface by the method described above. He then touched the sphere with another precisely equal sphere, and on again applying the proof-plane he found that the charge carried off by the plane was just half what it had been before.

423. Alternate Contact.—The above experiments naturally require some time, during which the body under investigation is gradually losing its charge. The consequence is, that the densities indicated by the balance, if taken singly, do not correctly represent the electric distribution. This source of error was avoided by Coulomb in the following manner. He touched two points on the body successively, and determined the electric density at each; and then, after an interval equal to that between the two experiments, he touched the first point again, and obtained a second measure of its density, which was less than the first, on account of the dissipation of electricity. If the densities thus observed be denoted by A and A′, and the density observed at the second point by B, it is evident that $\frac{A}{B}$ is greater, and $\frac{A'}{B}$ less than the ratio required. Coulomb adopted, as the correct value, their arithmetic mean $\frac{1}{2}\,\frac{A+A'}{B}$.

424. Power of Points.—The distribution of electricity on a conductor of any form may be roughly described, by saying that the density is greatest on those parts of the surface which project most, or which have the sharpest convexity, and that in depressions or concavities it is small or altogether insensible. Theory shows that at a perfectly sharp edge, such, for example, as is formed by two planes meeting at any angle however obtuse, but *not rounded off*, the density must be infinite, and *a fortiori* it must be infinite at a perfectly sharp point, for example at the apex of a cone, however obtuse, *if not rounded off*. Practically, the points and edges of bodies are always rounded off; the microscope shows them merely as places of very sharp convexity (that is, of very small radius of curvature), and hence the electric density at those places is really finite; but it is exceedingly great in comparison with the density at other parts, and this is especially true of very acute points, such as the point of a fine needle. The consequence is, that if a pointed conductor is insulated and charged, the concentration of a large amount of repulsive force within an exceedingly small area produces very rapid escape of electricity at the points. Conductors intended to retain a charge of electricity must have no points or edges, and must be very smooth. If of considerable length in proportion to their breadth, they are usually made to terminate in large knobs.

425. Dissipation of Charge.—When an insulated conductor is charged and left to itself, its charge is gradually dissipated, and at length completely disappears. This loss takes place partly through the supports, and partly through the air.

As regards the supports, the loss occurs chiefly at their surface, especially if (as is usually the case) they are not perfectly dry. It is diminished by diminishing their perimeter, and by increasing their length; for example, a long fibre of glass or raw silk is an excellent insulator.

As regards the air, we must distinguish between conduction and convection. Moist air and highly rarefied air probably act as conductors; but with air that is relatively dry the loss is probably chiefly due to contact and convection. Successive layers of air become electrified by contact with the conductor, and are then repelled, carrying off the electricity which they have acquired. It is by an action of this kind that electricity escapes into the air from points, as is proved by the wind which passes off from them (§ 444). Particles of dust present in the air, in like manner, act as carriers, being attracted to the conductor, charged by contact with it, and then repelled. They also frequently adhere by one end to the conductor, and thus constitute pointed projections through which electricity is discharged into the air.

Coulomb deduced from his observations on dissipation of charge, a law precisely analogous to Newton's law of cooling, namely, that when all other circumstances remain the same, *the rate of loss is simply proportional to the charge,* so that the charges at equal intervals of time form a decreasing geometric series. Subsequent experience has confirmed this law, as approximately true for moderate charges of the same sign. Negative charges are, however, dissipated more rapidly than positive.

CHAPTER XXXVIII.

ELECTRICAL MACHINES.

426. Electrical Machines.—The first electrical machine was invented by Otto Guericke, to whom, as we have already seen (§ 129), science is indebted for the invention of the air-pump. It consisted of a ball of sulphur which was turned upon its axis by one person, while another held his hands upon the ball, thus causing the friction necessary for the production of electricity. The result was that the globe was negatively electrified, and the positive electricity escaped into the earth through the hands of the operator. This machine, however, was capable of producing only very feeble effects, and the sparks obtained from it were visible only in the dark. An English philosopher, Hawksbee, substituted a globe of glass for the globe of sulphur; the electricity thus obtained was positive, and the sparks obtained by the new machine were of considerable brightness. The machine, however, was for the time superseded by the use of glass tubes, which continued to be the favourite instruments for generating electricity until the middle of the eighteenth century, when a German philosopher, Boze, professor of physics at Wittemberg, revived and perfected Hawksbee's machine, which became universally adopted.

Fig. 349, which is taken from the *Leçons de Physique* of the Abbé Nollet, published in 1767, shows the arrangement of the machine adopted by this celebrated philosopher. It consists of a large wheel, round which is passed an endless cord, which, passing also round a pulley, serves to turn a glass globe when the wheel is set in motion. The electricity thus produced is collected on a conductor suspended from the ceiling by silk cords.

It will be observed that, in the figure, the friction is produced by the hand. This mode of applying friction, which is evidently rude

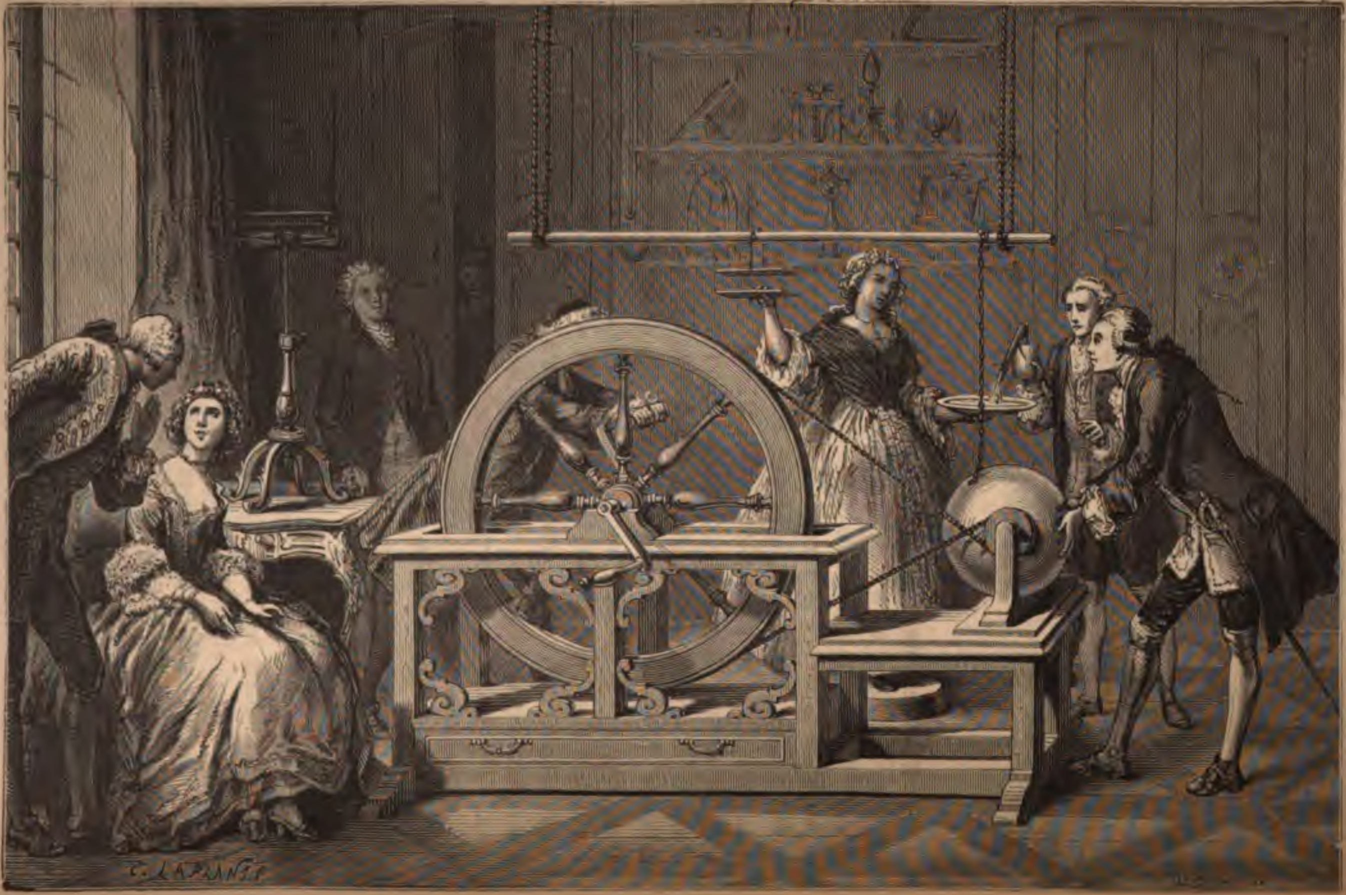

Fig. 249.—Hawksbee's Electrical Machine

and defective, was nevertheless long used for want of a better, though many attempts were made to replace it by the use of rubbers of leather, stuffed with hair, and pressed against the globe by means of regulating screws. The shape of the globe rendered the use of these very difficult, and it was not until a cylinder was substituted for the globe that they were generally adopted.

427. Ramsden's Machine.—The kind of machine most commonly employed at present is the plate-machine, invented by Ramsden about 1768, and only slightly changed and improved since.

The most usual form of this machine is shown in Fig. 350. It has a circular plate of glass, which turns on an axis supported by two wooden uprights. On each side of the plate, at the upper and lower parts of the uprights, are two cushions, which act as rubbers when the plate is turned. In front of the plate are two metallic conductors supported on glass legs, and terminating in branches, which are bent round the plate at the middle of its height.

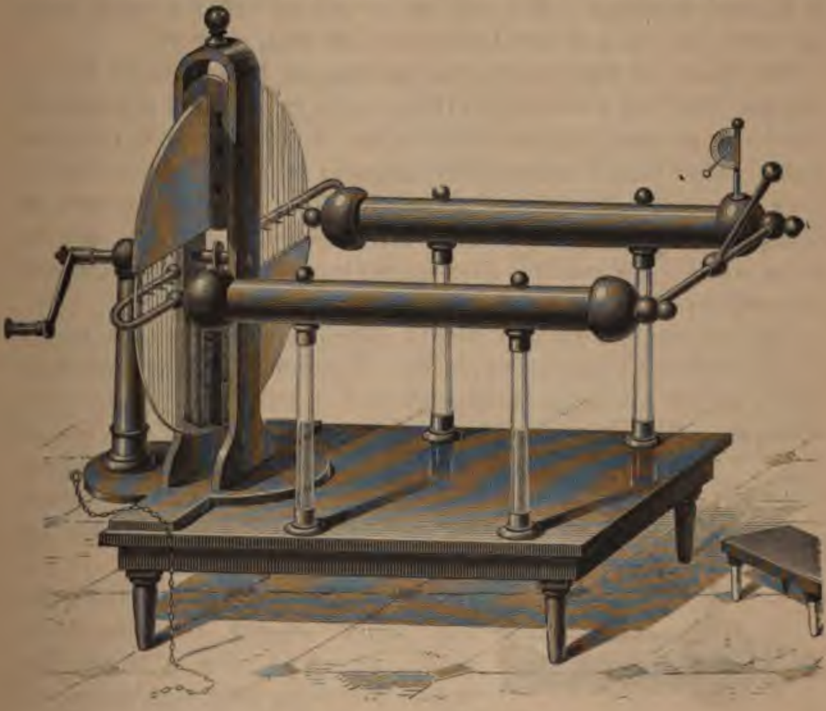

Fig. 350.—Ramsden's Electrical Machine.

and are studded with points projecting towards it. The plate becomes charged with positive electricity by friction against the cushions, and gives off its electricity through the points to the two conductors, or, what amounts to the same thing, the conductors give off negative electricity through the points to the positively-electrified plate. In order to avoid loss of electricity from that portion of the plate which is passing from the cushions to the points, sector-shaped pieces of oiled silk are placed so as to cover it on both sides. The cushions become negatively electrified by the friction; and the machine will not continue working unless this negative electricity is allowed to escape. The cushions are accordingly connected with the earth by means of metal plates let into their supports.

428. Limit of Charge.—As the conductors become more highly charged, they lose electricity to the air more rapidly, and a time soon arrives when they lose electricity as fast as they receive it from the plate. After this, if the machine continues to be worked uniformly, their charge remains nearly constant. This limiting amount of charge depends very much upon the condition of the air; and in damp weather the machine often refuses to work unless special means are employed to keep it dry.

The rubbers are covered with a metallic preparation, of which several different kinds are employed. Sometimes it is the compound called *aurum musivum* (bisulphide of tin), but more frequently an amalgam. Kienmeier's amalgam consists of one part of zinc, one of tin, and two of mercury. The amalgam is mixed with grease to make it adhere to the leather or silk which forms the face of the cushion.

Before using the machine, the glass legs which support the conductors should be wiped with a warm dry cloth. The plate must also be cleaned from any dust or portions of amalgam which may adhere to it, and lastly, dried with a hot cloth or paper. When these precautions are taken, the machine, if standing near a fire, will always work; but the charging of Leyden jars, and especially of batteries, may be rendered impossible by bad weather.

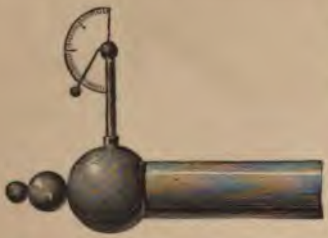

Fig. 351.—Quadrant Electroscope.

The variations of charge are indicated by the *quadrant electroscope* (Fig. 351), which is attached to one of the conductors. It consists of an upright conducting stem, supporting a quadrant, or more commonly a semicircle, of ivory, at whose centre a light needle of ivory is jointed, carrying a pith-ball at its end. When there is no charge in the conductor, this pendulum hangs vertically, and as the charge increases it is repelled further and further from the stem. In damp weather it will be observed to return to the vertical position almost immediately on ceasing to turn the machine, while in very favourable circumstances it gives a sensible indication of charge after two or three minutes.

429. Nairne's Machine.—Ramsden's machine furnishes only positive electricity. In order to obtain negative electricity, it is necessary to insulate the cushions from the ground, and to place them in communication with an insulated conductor. An arrangement of this kind is adopted in Nairne's machine.

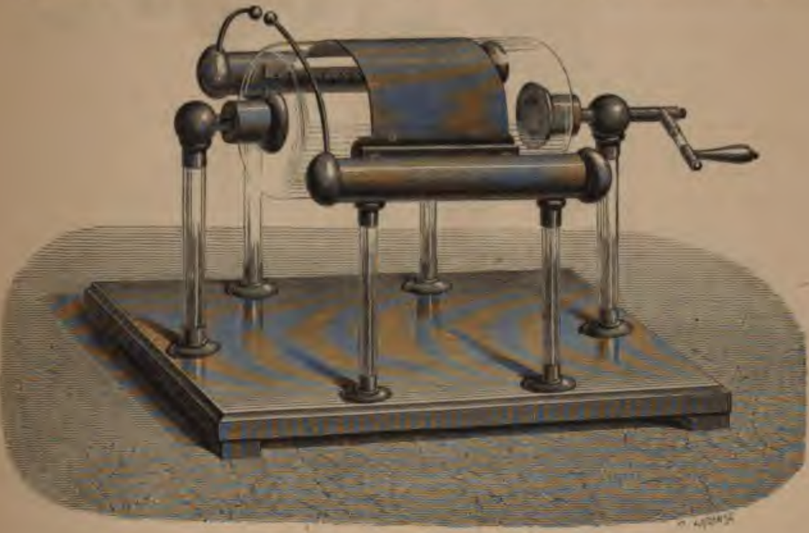

Fig. 352.—Nairne's Electrical Machine.

In this machine a large cylinder of glass revolves between two separately insulated conductors. One of these has a row of points projecting towards the glass, and collects positive electricity. The other is connected with the rubber, and collects negative. If one kind of electricity only is required, the conductor which furnishes the other must be connected with the ground.

430. Winter's Machine.—Winter, of Vienna, has introduced some modifications in Ramsden's machine.

Instead of four cushions, there are, as will be seen by the figure (Fig. 353), only two, which are in communication with a spherical conductor, supported on a glass pillar. This may be used to collect negative electricity, in the same way as the negative conductor in Nairne's machine. The chief or positive conductor consists of an insulated sphere, on the top of which is often another sphere of smaller size. The positive electricity is collected from the plate by means of two rings opposite to each other, one on each side of the plate. On the side next the plate, they have a groove, which is lined with metal, and studded with points. They are supported by an arm which is inserted in the positive conductor. The size of the positive conductor is often increased by the addition of a very large ring (3 or 4 feet in diameter) which is supported on the top of the large sphere. The ring consists of very stout brass wire inclosed in well-polished mahogany.

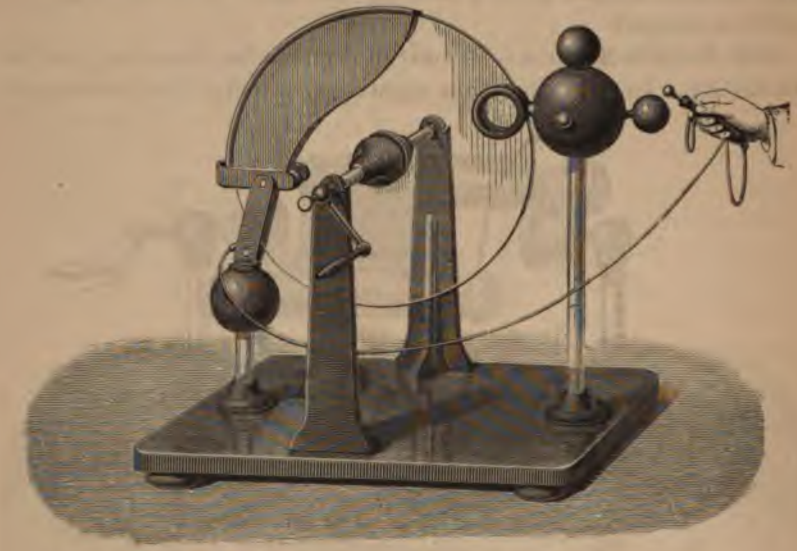

Fig. 353.—Winter's Electrical Machine.

Winter's machine appears to give longer sparks than the ordinary machine under the same circumstances. This circumstance is owing, partly at least, to the considerable distance between the rubber and the positive conductor, which prevents the occurrence of discharges between them.

431. Hydro-electric Machine.—About the year 1840, Mr. (now Sir) W. Armstrong invented an electric machine, in which electricity was generated by the friction of steam against the sides of orifices, through which it is allowed to escape under high pressure. It consists of a boiler with the fire inside, supported on four glass legs. The steam, before escaping, passes through a number of tubes which traverse a cooling-box containing water, into which dip meshes of cotton, which are led over the tubes, and passed round them. The cooling thus produced in the tubes, causes partial condensation of the steam. This has been found to be an indispensable condition, the friction of per-

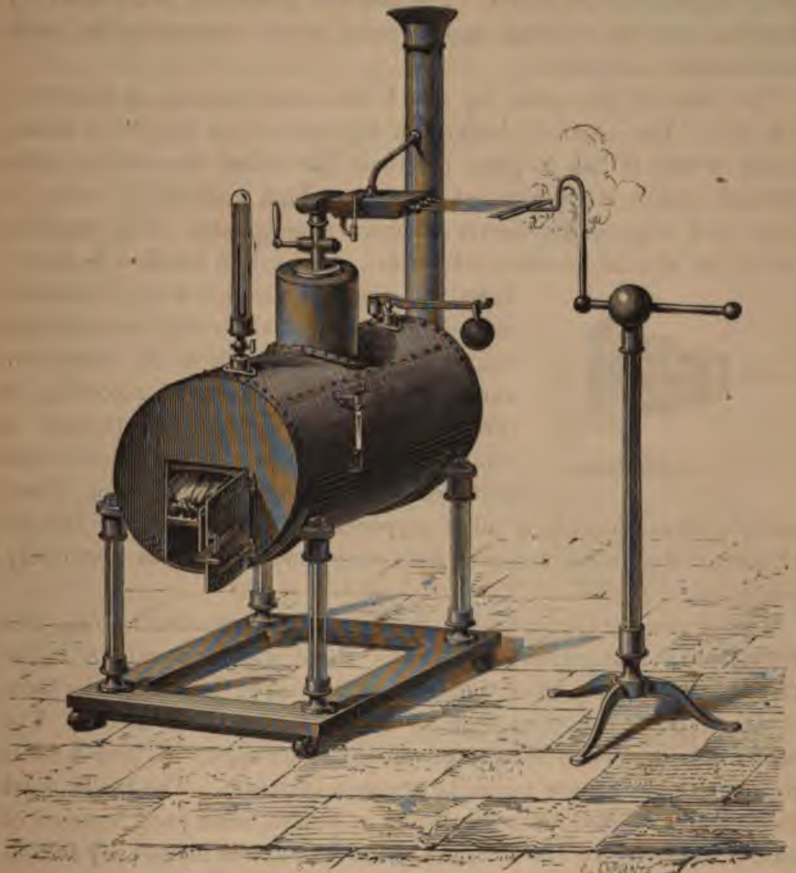

Fig. 354.—Armstrong's Hydro-electric Machine.

fectly dry steam being quite inoperative. Speaking strictly, it is the friction of the drops of water against the sides of the orifice, which generates the electricity, and the steam merely furnishes the means of applying the friction. The jet of steam is positively, and the boiler negatively electrified. The positive electricity is collected by directing the jet of steam upon a metal comb communicating with an insulated conductor.

The form of the outlet by which the steam escapes is shown in Fig. 355. The steam is checked in its course by a tongue of metal, round which it has to pass, before it can enter the wooden tube through which it escapes into the air. This machine, in order to work well, requires a pressure of several atmospheres. The water in the boiler should be distilled water. If a saline solution be introduced into the tube through which the steam escapes, all traces of electricity immediately disappear. The generation of electricity varies both in sign and degree, according to the substance of which the escape-tube is composed, and according to the liquid whose particles are carried out by the steam. Thus, when a small quantity of oil of turpentine is introduced into the jet of steam, the boiler becomes positively, and the steam negatively electrified.

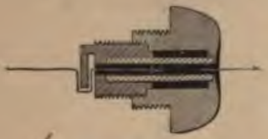

Fig. 355.—Outlet of Steam.

The hydro-electric machine is exceedingly powerful. At the Polytechnic Institution in London, there was one with a boiler 78 inches long and 42 in diameter, and with 46 jets. Sparks were obtained from the conductor at the distance of 22 inches. The machine is, however, very inconvenient to manage. A long time is required to get up the requisite pressure of steam. The boiler must be carefully washed with a solution of potash, after each occasion of its use; and, finally, the working of the machine is necessarily accompanied by the disengagement of an enormous quantity of steam, which, besides causing a deafening noise, has the mischievous effect of covering with moisture everything within reach. Accordingly, though very interesting in itself, it is by no means adapted to the general purposes of an electrical machine.

432. Holtz's Machine.—In the machines just described, electricity is produced by the friction of one substance against another. Quite recently, several machines have been invented of quite a different kind, in which a body is electrified once for all, and made to act by induction upon a movable system, in such a way as to produce a continual generation of electricity. The most successful of these is that invented by Holtz of Berlin in 1865.

It contains two thin circular plates of glass, one of which, A, is fixed, while the other, B, which is rather smaller, can be made to revolve very near it. In the fixed plate there are two large holes or windows near the extremities of its horizontal diameter. Across these, and partly covering them, are glued two paper bands or armatures, having points *f*, *f′* directed the opposite way to that in which the movement takes place. Two metallic combs P, P′ are placed opposite the windows, on the other side of the revolving plate, and are connected with two insulated conductors terminating in the knobs *n*, *m*, which may be called the poles or electrodes of the machine. These knobs can be set at any distance asunder. In starting the machine, they are placed in contact, and one of the armatures, suppose *f*, is electrified by holding against it a sheet of vulcanite which has been charged with negative electricity by fric-

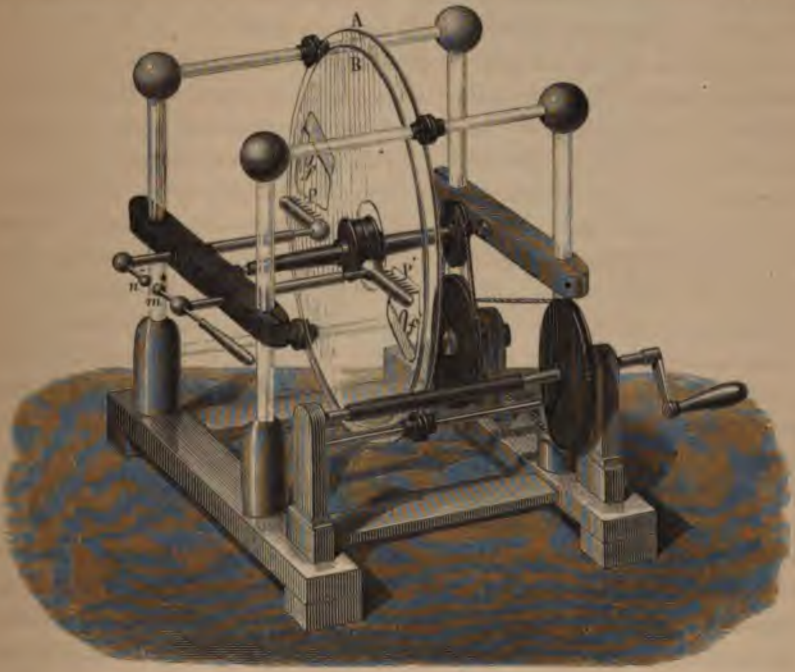

Fig. 356.—Holtz's Electrical Machine.

tion. The plate is then turned for a few seconds, and the two knobs are gradually separated.

A continuous crackling noise is immediately produced at the place of separation, resulting from electric discharge across the interval. In the circumstances supposed, the knob *n* is the negative, and the knob *m* the positive electrode. In dry weather, the machine, when once started, will continue in action for a long time if the motion is kept up, but it soon ceases to act if the air is damp, being even more sensitive to moisture than the ordinary machine.

The action of the machine is as follows:—The negative electricity of the armature *f*, acting inductively on the opposed conductor, from which it is separated by the revolving plate, causes this conductor to discharge positive electricity, through the comb, upon the face of the plate, and thus to acquire a negative charge; when the part of the plate which has been thus affected comes opposite the other armature, the latter is affected inductively, and discharges negative electricity through its point *f′* upon the back of the plate, thus becoming itself positively electrified. Positive electricity from the front of the plate is at the same time collected by the comb P′, an equal quantity of negative being of course discharged from the comb upon the plate. In the subsequent stages of the process, the negative electricity thus discharged upon the face of the plate exceeds the positive which was previously there, so that the face of the plate passes on with a negative charge. When the portion of the plate which we are considering again comes opposite *f*, it increases the negative electrification both of the armature and the conductor, inasmuch as it has more of negative or less of positive electricity upon both its surfaces than it had when it last moved away from that position. Both armatures thus become more and more strongly electrified, until a limit is attained which depends on the goodness of the insulation; and as the electrification of the armatures increases, the conductors also become more powerfully affected, and are able to discharge to each other by the knobs *m n* at a continually increasing distance.

The inventor has recently introduced a modified form of his machine. The plates are placed horizontally (Fig. 357), they have neither windows nor armatures, and they both revolve, but in opposite directions. Two conductors furnished with rows of points are placed above the upper plate at the extremities of one diameter, and two others below the lower plate at the extremities of another diameter perpendicular to the former. Each of the upper conductors is connected with one of the lower, so that there are virtually only two conductors. In starting the machine, a sector of electrified vulcanite is held over the upper plate, opposite one of the lower combs. When the machine has been turned for a few seconds, the sector may be removed, and a continual discharge of sparks takes place between the two knobs which are connected with the two conducting systems. Frequently, as in the figure, a comb is placed above, opposite to the lower comb, and this arrangement appears to increase the efficiency of the machine.

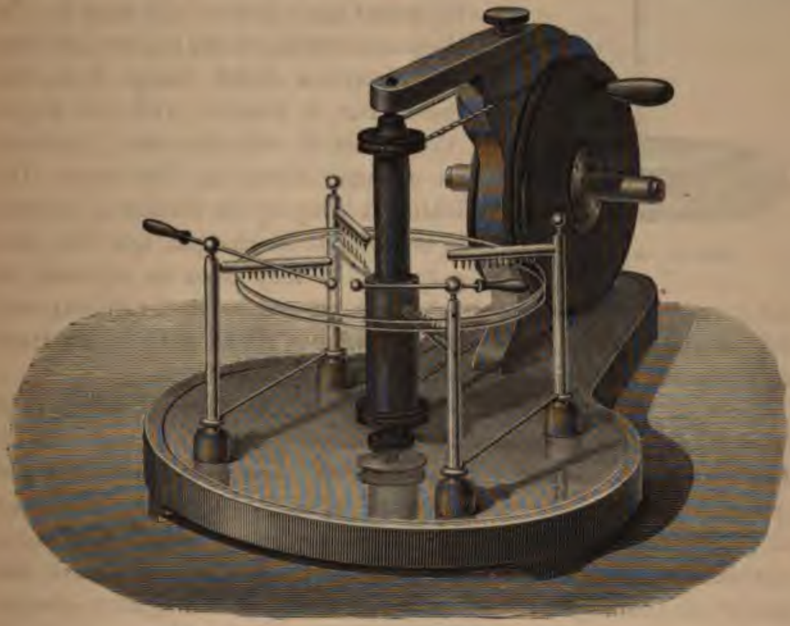

Fig. 357.—Holtz's Machine with Horizontal Plates.

The action in this form of the machine also depends upon induction, the conductors performing the duty of armatures as well. We shall not enter into details, but merely remark that, in both forms of the machine, work is spent in turning the plates in opposition to electrical attractions and repulsions; and that the mechanical energy thus consumed produces an equivalent in the form of electrical energy.

433. Electrophorus.—When electricity is required in comparatively small quantities, it is readily supplied by the simple apparatus called the *electrophorus.* This consists (Fig. 358) of a disc of resin, or some other material easily excited by friction, and of a polished metal disc B with an insulating handle CD. The resin disc is electrified by striking or rubbing it with catskin or flannel, and the metal plate is then laid upon it. In these circumstances, the upper plate does not receive a direct charge from the lower, but, if touched with the finger (to connect it with the earth), receives an opposite charge by induction. On lifting it away by its insulating handle, it is found to be charged, and will give a spark. It may then be replaced on the lower plate (touching it at the same time with the finger), and the process repeated an indefinite number of times, without any fresh excitation, if the weather is favourable.

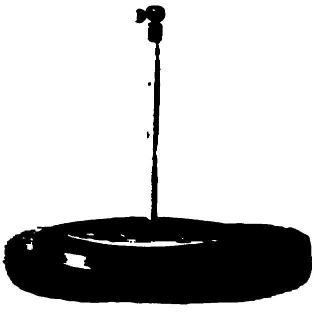

Fig. 358.—Electrophorus.

The resinous plate has usually a base or *sole* of metal, which is in connection with the earth while the electrophorus is being worked. This sole, by the mutual induction which takes place between it and the upper plate or *cover*, increases the capacity of the latter (see Chap. xl.), and thus increases the charge acquired. When the cover receives its positive charge on being connected with the earth, the sole at the same time receives from the earth a negative charge, and as the cover is gradually lifted this negative charge gradually returns to the earth.

The most convenient form of the electrophorus is that of Professor Phillips, in which the cover, when placed upon the resinous plate, comes into metallic connection with the metal plate below. That this arrangement is allowable is evident, when we reflect that, when the upper plate is touched with the finger, it is in fact connected with the lower plate, since both are connected with the earth; and it effects a great saving of time when many sparks are required in quick succession, for the cover may be raised and lowered as fast as we please, coming alternately into contact with the resinous plate and the body which we wish to charge.

434. Bertsch's Electrical Machine.—A machine which has been called a rotatory electrophorus has recently been invented by Bertsch, and is represented in Fig. 359. A circular plate of ebonite D can be made to revolve rapidly. A sector of the same material, previously excited by friction, is fixed opposite the lower portion of the plate; and on the other side, immediately opposite to this, is a metallic comb N forming the extremity of a conductor connected with the earth. At the upper part is another comb M connected with the conductor A. Under the influence of the electrified sector, the conductor C discharges positive electricity on the plate through the comb N. In passing the comb M, a portion of this electricity is collected by the points, and charges the conductor A. The effect is increased by connecting A with another conductor E of very large dimensions.

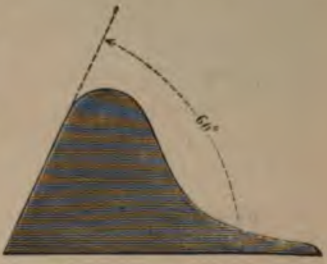

Fig. 359.—Electrified Sector.

This machine differs from that of Holtz in furnishing no means for increasing, or even sustaining, the charge of the armature. In this respect it resembles the ordinary electrophorus.

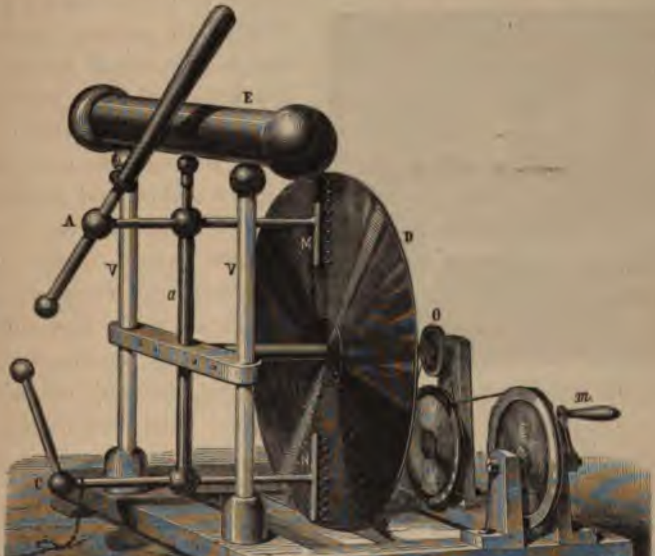

Fig. 360.—Bertsch's Electrical Machine.

CHAPTER XXXIX.

VARIOUS EXPERIMENTS WITH THE ELECTRICAL MACHINE.

435. Electric Spark.—The spark furnished by an electrical machine of small dimensions is short, and usually straight. Powerful machines sometimes give sparks of the length of a foot. Such sparks have usually a zig-zag form, like flashes of lightning. One of the readiest means of obtaining long sparks consists in placing, opposite to one of the small knobs of the conductor of the machine, a large conductor, having good earth connection, and presenting a polished and slightly convex surface towards the knob. A more powerful effect will be obtained by connecting this conductor with the rubber or the negative conductor of the machine, instead of with the earth. Very frequently, when the spark is a foot or more in length, finer ramifications proceed from its main track, as shown in Fig. 362.

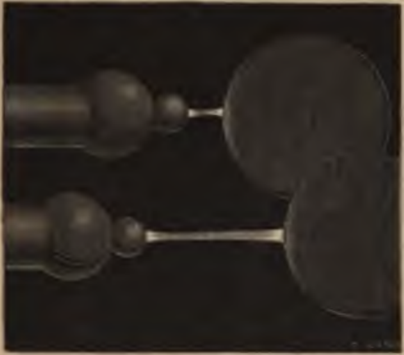

Fig. 361.—Electric Spark.

436. Brush.—When a powerful machine is working in a very dry atmosphere, the rubbers being in good order, and the machine being turned rapidly, a characteristic sound is heard, which is an indication of continuous discharge into the air. In the dark, luminous appearances called *brushes* are seen on the projecting parts of the conductors. They may be rendered very conspicuous by presenting a large conducting surface at a distance a little too great for a spark to pass. It will then be observed that the brush consists (Fig. 363) of a short foot-stalk, with a multitude of rays diverging from it like a fan, and with other smaller ramifications proceeding from these. Positive electricity gives larger and finer brushes than negative. We may add, that, when the machine is working well, brilliant sparks continually leap across the plate, consisting of discharges between the cushions and the nearest part of the conductor. The conductor itself is also surrounded with luminosity. In the dark, the brilliant spectacle presented by these combined appearances, with the continual crackling which accompanies them, is very impressive, and furnished an inexhaustible subject of curiosity to the electricians of last century.

It is probable that the passage of a spark is always preceded by a very high degree of polar tension in all the particles of air in and about its track, and that the spark occurs when this tension anywhere exceeds what the particles are able to bear. The frequent crookedness of the spark is probably

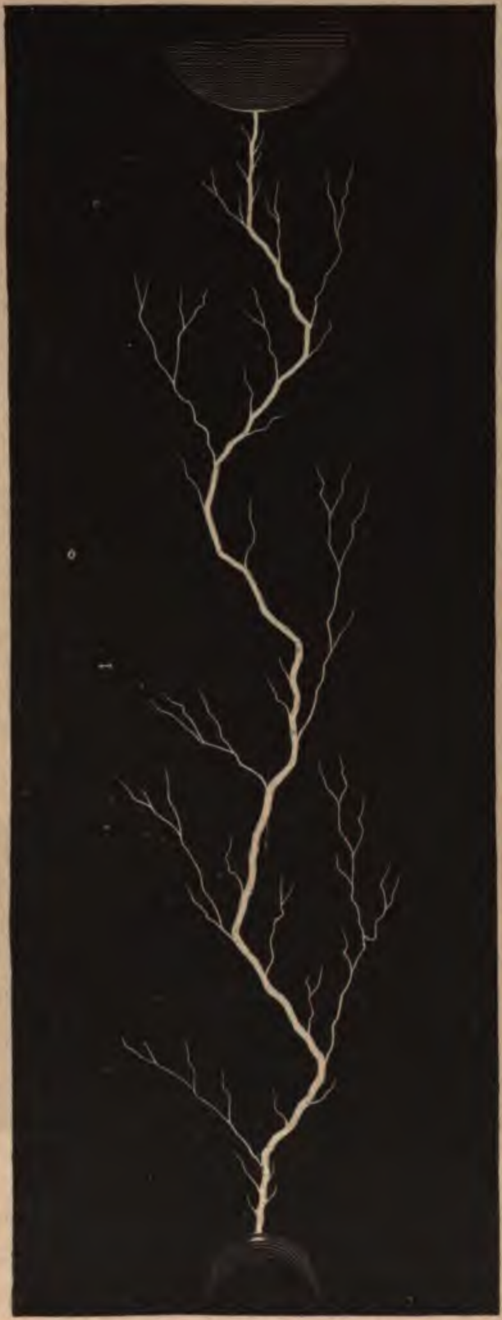

Fig. 362.—Spark with Ramifications.

due to the presence of conducting particles of dust, which serve as stepping-stones, and render a crooked course the easiest.

437. Duration of the Spark.—We can form no judgment of the duration of the electric spark from what we see with the unaided eye; for impressions made upon the retina remain uneffaced for something like $\frac{1}{10}$ of a second, and the duration of the spark is incomparably less than this. Wheatstone, in a classical experiment, succeeded

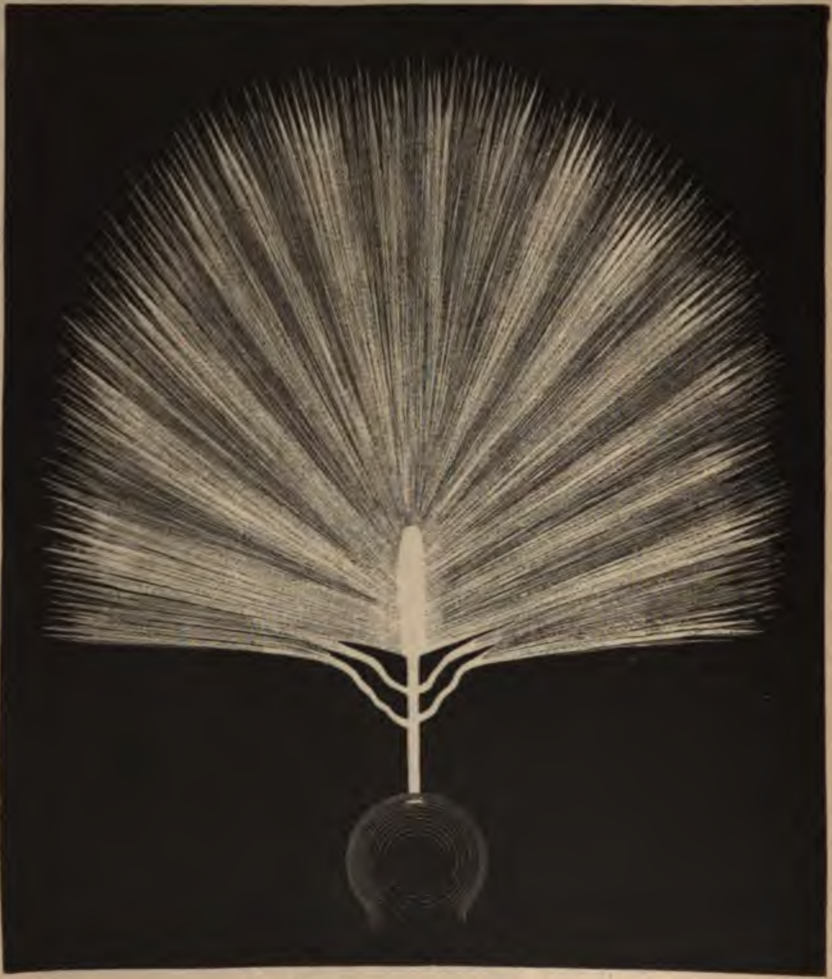

Fig. 363.—Electric Brush, after Van Marum.

in measuring its duration by means of a revolving mirror; an expedient which has since been employed with great advantage in many other researches, especially in determining the velocity of light.

Let *mn* (Fig. 364) be a mirror revolving with great velocity about an axis passing through *c*, and suppose that, during the rotation, an electric spark is produced at *a*. An eye stationed at *o* will see an image in the symmetrical position a'. If the spark is strictly instantaneous, its image will be seen as a luminous point at a', notwithstanding the rotation of the mirror; but if it has a finite duration, the image will move from a' to a'', while the mirror moves from ee' to tt', the latter being its position when the spark ceases. What is actually seen in the mirror will therefore not be a point, but a luminous track $a'a''$.

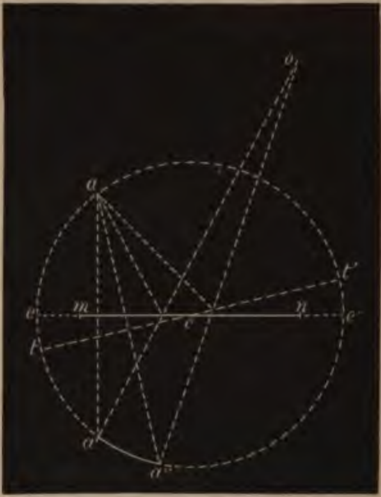

Fig. 364.—Duration of Spark.

The length of this image will be double of the arc *et*; for the angle *ect* at the centre is equal to the angle $a'aa''$ at the circumference, the sides of the one being perpendicular to those of the other. In Wheatstone's experiment, the mirror made 800 turns in a second, and the image $a'a''$ was an arc of 24°; the mirror therefore turned through 12°, or $\frac{1}{30}$ of a revolution, while the spark lasted. The duration of the spark was therefore $\frac{1}{30}$ of $\frac{1}{800}$, that is, $\frac{1}{24000}$ of a second.

By examining the brush in the same way, Wheatstone found it to consist of a succession of sparks.

438. Spark in Rarefied Gases.—The appearance of the spark is greatly modified by rarefying the air in which it is taken. To show this, an apparatus is employed which is called the *electric egg*. It is an oval glass vessel, which can be exhausted by means of a stop-cock at its lower end. Its upper end is closed by a cap, in which slides a brass rod terminated by a knob, which can be adjusted to any distance from another knob connected with a cap at the lower end.

When the egg contains air at atmospheric pressure, a spark passes in the ordinary way between the two knobs; but, as the pressure is diminished, the aspect of the spark changes. At a pressure of six centimetres of mercury ($\frac{1}{13}$ of an atmosphere), a sort of ramified sheaf proceeds from the positive knob, some of the rays terminating at a small distance from their origin, while others extend to the negative knob. The latter is surrounded with a violet glow; the rays are also violet, but with a reddish tinge. The light at the positive knob is of a reddish purple.

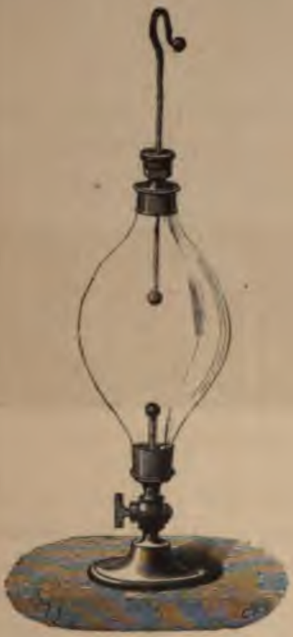

Fig. 365.—Electric Egg.

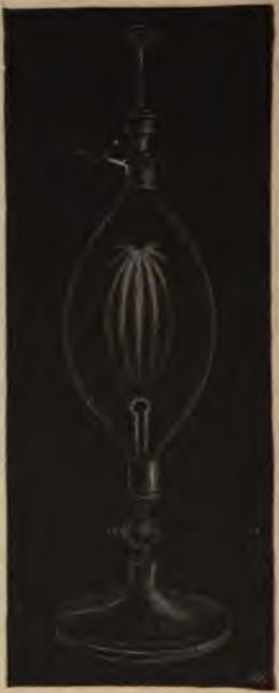

Fig. 366.—Spark in Rarefied Air.

As the pressure is gradually reduced to a few millimetres, the rays become less distinct, and finally coalesce into an oval cloud of pale violet light, extending from one knob to the other, with a reddish tint at the positive and a deep violet at the negative end.

In performing this experiment with the ordinary electrical machine, the upper knob is connected with the conductor, and the lower one with the ground. Holtz's machine can be very advantageously employed in experiments of this kind, its two poles being connected with the two knobs.

When, instead of the electric egg, we employ a long tube, such as is employed for showing the fall of bodies *in vacuo*, the whole length of the tube is filled with violet light, which exhibits continual flickering, and suggests the idea of undulations travelling in the same direction as the positive electricity. In all these experiments, as we diminish the density of the air, we diminish the resistance to discharge, and at the same time diminish the intrinsic brightness of the spark.

In the Torricellian vacuum, electric discharge is accompanied by a perceptible though very feeble luminosity, as may be shown by an arrangement due to Cavendish, and represented in Fig. 367. Two barometric tubes, united at the top, are plunged in two cups of mercury. The mercury in one cup is connected with the conductor of the machine, while that in the other is connected with the earth. In these circumstances, the vacuum-space is filled with luminosity, which is brighter as the temperature is higher, probably on account of the greater density of the mercurial vapour which serves as the medium of discharge.

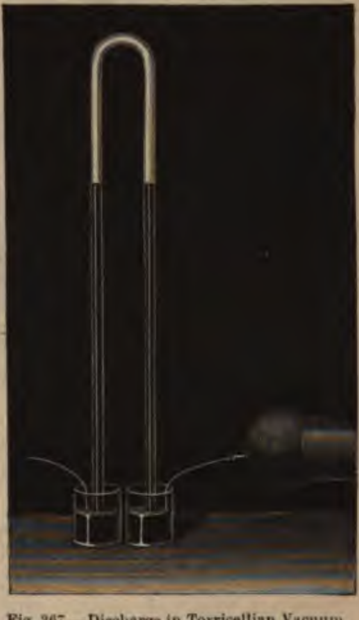

Fig. 367.—Discharge in Torricellian Vacuum.

The experiments of Gassiot and others have shown that electricity traverses a space occupied by a gas with continually increasing facility as the density of the gas is diminished, until a certain limit is attained; but that when special means are employed to render the vacuum as nearly perfect as possible, this limit can be exceeded, and the resistance may increase so much as to prevent discharge.

This latter point is illustrated by the apparatus represented in Fig. 368, which is constructed by Alvergniat. T is a tube which has been exhausted as completely as possible by a Geissler's pump. It has then been heated, and maintained for some time near the temperature of fusion of glass, in order to produce absorption of the remaining air. Two platinum wires have been previously sealed in the ends of the tube, and approach within $\frac{1}{10}$ of a millimetre of each other. The two poles of a Holtz's machine are connected with the binding-screws B and B′, which are in communication with these two wires, and also with two rods whose extremities *p p′* are at a moderate striking distance from each other in air. As long as the machine works, sparks pass between these latter, while, in spite of the very much closer proximity of the platinum wires, no luminosity is perceptible between them. Instead of being placed a small distance apart in air, *p* and *p′* may be fitted into the ends of a tube of considerable length containing rarefied air. It will be found that discharge can take place at greater distance as the air is more rarefied, till we attain a limit far beyond the reach of ordinary air-pumps.

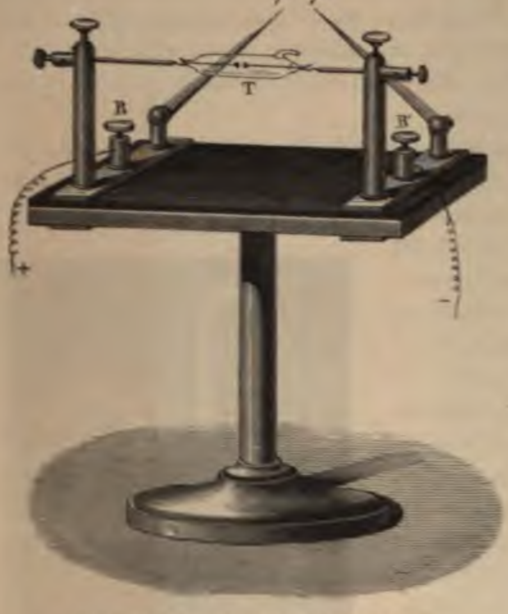

Fig. 368.—Non-conductivity of Perfect Vacuum.

439. Colour of the Spark.—The colour of the spark or other luminous discharge depends partly on the material of the conductors between which it passes, and partly on the gaseous medium which it traverses. The former influence predominates when the spark is strong, the latter when it is weak. The effect of the metal seems to depend upon the vaporization of a portion of it, for, on examining the spark by the spectroscope, bright lines are seen which are known to indicate the presence of metallic vapour. For studying the effect of the gaseous medium, the discharge is taken between two platinum wires sealed into the ends of glass tubes, containing the gases in a rarefied condition. The wires are connected either with the poles of a Holtz's machine, or of a Ruhmkorff's coil, which we shall describe in Chap. lii. It is found that the colour in air or oxygen is white with a tinge of blue, in nitrogen blue, in hydrogen red, and in carbonic acid green.

440. Multiplication of the Electric Spark.—The old electricians contrived several pieces of apparatus for multiplying the electric spark. The principle of all is the same. Small squares of tin-foil are arranged in series at a small distance from each other on an insulating surface. The first of the series is connected with a metallic knob which can be brought near the electrical machine; and the last of them is connected with another knob which is in communication with the earth. By allowing a discharge to pass through the series, sparks can be simultaneously obtained at all the intervals between the successive squares.

In the *spangled tube* (Fig. 370) the squares of tin-foil are arranged spirally along a cylindrical glass tube which has a brass cap at each end. One cap is put in communication with the machine, and the other with the earth.

Sometimes a glass globe is substituted for the cylinder. We have thus the *spangled globe* (Fig. 371).

In the *sparkling pane* a long strip of tin-foil is disposed in one continuous crooked line (consisting of parallel strips connected at alternate ends) from a knob at the top to another knob at the bottom of the pane. A pattern is then traced by scratching away the tin-foil in numerous places with a point, and when the spark passes, it is seen at all these places, so as to render the pattern luminous (Fig. 372).

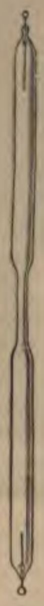
Fig. 369.—Tube for Rarefied Gases.

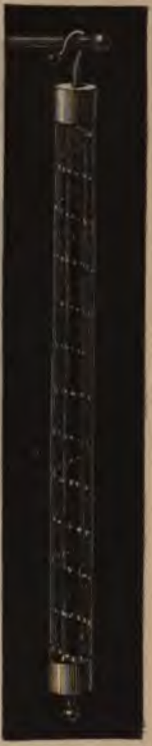
Fig. 370. Spangled Tube.

441. Physiological Effects of the Spark: Electric Shock.—When a strong spark is drawn by presenting the hand to the conductor of a very large and powerful machine, a peculiar sensation is experienced. With ordinary machines the same effect can be obtained by employing a Leyden jar. The sensation is difficult to describe, and only capable of being produced by electrical agency. It is a painful shock, felt especially in the arm, and causing an involuntary bending of the elbow.

At the distance of a few feet from a machine in powerful action, a tickling sensation is felt on the exposed parts of the body, due to the movement of the hairs in obedience to electrical force. These phenomena are exhibited in a still more marked manner when a person stands on a stool with glass legs, and keeps his hand upon the conductor. He thus becomes highly charged with electricity. His hair stands on end, and is luminous if seen in the dark. If a conductor connected with the earth is presented to him, a spark passes, and his hair falls again.

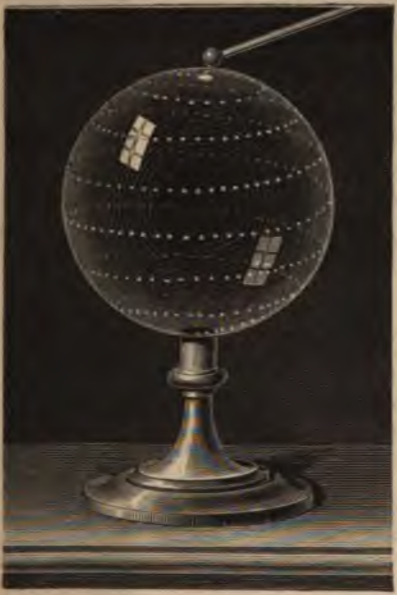

Fig. 371.—Spangled Globe.

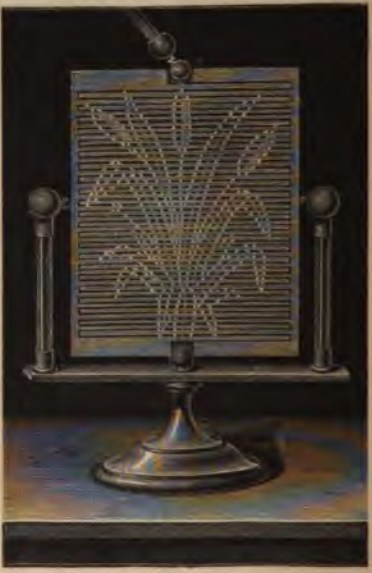

Fig. 372.—Spangled Pane.

Electricity has frequently been resorted to for medical purposes. The electrical machine was first employed, and afterwards the Leyden jar, but both have now been abandoned in favour of magneto-electric machines and induction coils, which we shall describe in a later chapter (Chap. lii.)

442. Mechanical and Physical Properties of the Spark.—The electric spark produces a violent commotion in the medium in which it occurs. This is easily shown by means of Kinnersley's thermometer (Fig. 373), which consists of two glass tubes of unequal diameters, the smaller being open at the top, while the larger is completely closed, with the exception of a side passage, by which it communicates with the smaller. The caps which close the ends of the large tube are traversed by rods terminating in knobs, and the upper one can be raised and lowered to vary the distance between the knobs. Both tubes are filled, to a height a little below the lower knob, with a very mobile liquid such as alcohol. When the spark passes between the knobs, the liquid is projected with great violence, and may rise to a height of several yards if the spark is very strong. The same property of the spark is exhibited in the experiment of the electric mortar, which is sufficiently explained by the figure (Fig. 374).

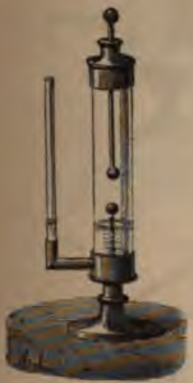

Fig. 373.—Kinnersley's Thermometer.

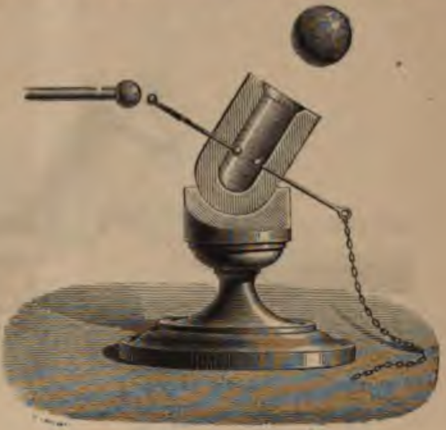

Fig. 374.—Electric Mortar.

The spark may be obtained in the interior of a non-conducting liquid, which it agitates in a similar manner. If the liquid is contained in a closed vessel, this is often broken. The spark can also traverse thin non-conducting plates, producing in this case perforation of the plates; but the experiment usually requires very powerful discharges, such as can only be obtained by means of apparatus described in the next chapter.

The luminosity of the electric spark is probably due to the very high temperature which is produced in the particles traversed by the discharge. Coal-gas is easily inflamed, by a person standing on a stool with glass legs holding one hand on the conductor of the machine, and giving sparks from a finger of the other hand to the burner from which the gas is issuing. Kinnersley regarded elevation of temperature as the cause of the movement of the liquid in his apparatus; hence the name which it bears.

Heating may also occur in the case of conductors. This is shown by the influence of the metal upon the colour of the spark, and it may be more directly proved by arranging a conductor in communication with the earth, and connected by an exceedingly fine metallic wire with another conductor. When the latter is presented to a very powerful electrical machine, so that a strong spark passes, the fine wire is sometimes heated to redness.

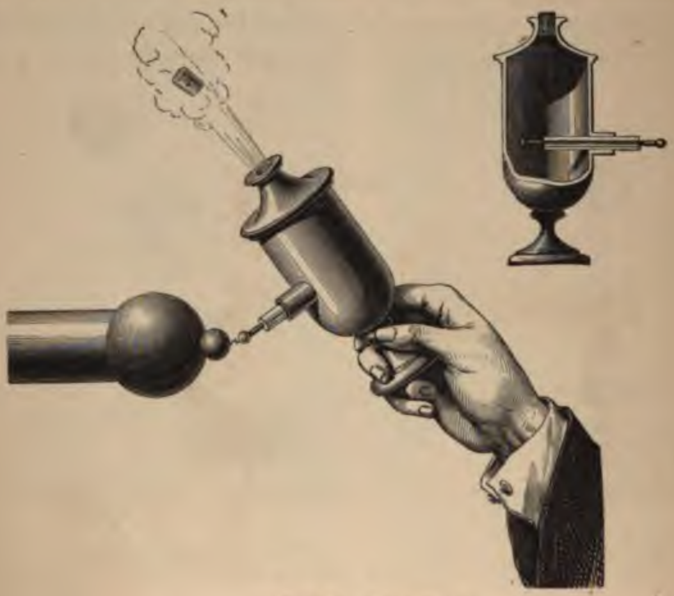

Fig. 375.—Volta's Pistol.

443. Chemical Properties of the Spark.—The electric spark is able to produce very important chemical effects. When it occurs in an explosive mixture of two parts of hydrogen with one of oxygen, it causes these gases instantly to combine. This experiment is usually shown by means of Volta's pistol (Fig. 375), which is a metallic vessel, containing the mixture, and closed by a cork. Through one side passes an insulated metallic rod with a knob at each end, that at the inner end being at a short distance from the opposite side of the vessel, so that, if a spark is given to the exterior knob, a spark also passes in the interior, and inflames the mixture. This effect is accompanied by a violent detonation, and the cork is projected to a distance.

The electric spark often produces a reverse effect—that is to say, the decomposition of a compound body; but the action in this case is gradual, and a great number of sparks must be passed before the full effect is obtained. Thus, if a succession of sparks be passed in the interior of a mass of ammonia, contained in a vessel inverted over mercury, the volume of the gas is observed to undergo a gradual increase, until at length, if kept at constant pressure, the volume is exactly doubled. It then consists of a mechanical mixture of nitrogen and hydrogen, the constituents of ammonia.

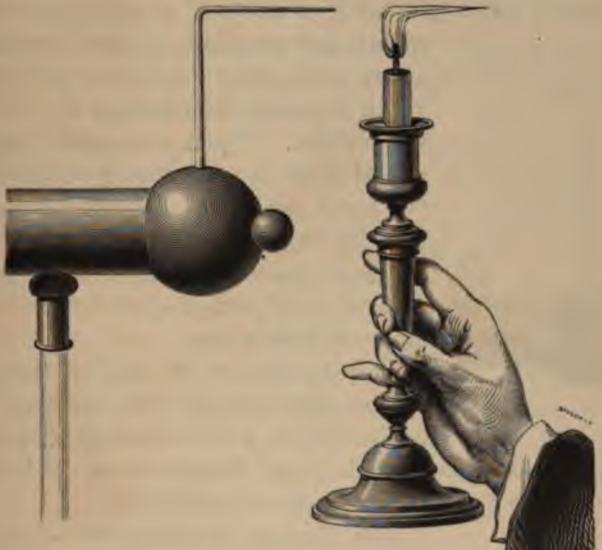

Fig. 376.—Wind from Points.

Composition and decomposition are often both produced at once. Thus, if a spark is passed in a mixture of carburetted hydrogen and a certain proportion of oxygen, the former gas is decomposed, its hydrogen combining with a portion of the oxygen to form water, and its carbon combining with another portion to form carbonic acid.

Vessels intended for taking the electric spark in gases are extensively used in chemistry, and are called *eudiometers*.

444. Wind from Points.—If a metallic rod terminating in a point be attached to the conductor of the electrical machine, electricity escapes in large quantity from the point, which, accordingly, when viewed in the dark, is seen to be crowned with a tuft of light. A layer of air in front of the point is electrified by contact, and then repelled, to make way for other portions of air, which are in their turn repelled. A continuous current of air is thus kept up, which is quite perceptible to the hand, and produces a very visible effect on the flame of a taper (Fig. 376).

The *electric whirl* (Fig. 377) consists of a set of metallic arms, radiating horizontally from a common centre about which they can turn freely, and bent, all in the same direction, at the ends, which are pointed. When the central support is mounted on the conductor of the machine, the arms revolve in a direction opposite to that in which their ends point. This effect is due to the mutual repulsion between the pointed ends and the electrified air which flows off from them.

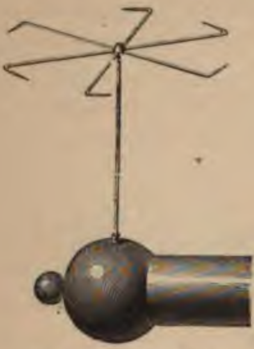
Fig. 377.—Electric Whirl.

It is instructive to remark that if, by a special arrangement, the rotating part be inclosed in a well-insulating glass case, the rotation soon ceases, because, in these circumstances, the inclosed air quickly attains a state of permanent electrification.

445. Electric Watering-pot.—Let a vessel containing a liquid, and furnished with very fine discharge tubes, be suspended from the conductor of the machine. When the vessel is not electrified, the liquid comes out drop by drop; but when the machine is turned, it issues in continuous fine streams. It has, however, been observed that the quantity discharged in a given time is sensibly the same in both cases. This must be owing to the equality of action and reaction between different parts of the issuing stream.

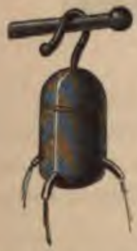
Fig. 378.—Electric Bucket.

CHAPTER XXXIX^A.

ELECTRICAL POTENTIAL, AND LINES OF ELECTRIC FORCE.

445A. Introductory Remarks on Potential.—Electrical reasonings are, in many cases, greatly facilitated by employing the conception denoted by the name *electrical potential*.

Potential essentially depends upon forces (whether attractive or repulsive) mutually exerted upon each other by particles at a distance, and has been advantageously employed in the theories of gravitation and magnetism, as well as of electricity. We shall at present confine our attention to *electrical* potential.

All the space in the neighbourhood of electrified bodies is in a certain sense pervaded by their influence. This influence is completely specified by stating the numerical values, with proper sign, of electrical potential, at the different points of the space.

Electrical potential never changes its value *per saltum* in passing from one point to the next. Moreover, if it is constant in value throughout any finite portion of a space not containing electricity, it is constant throughout the whole of this space.

445B. Relation of Potential to Force.—When electrical potential is constant throughout a given space, there is no electrical force[1] in that space; and, conversely, if there be an absence of electrical force in a given space, the potential throughout that space must be uniform. These propositions apply to the space within a hollow conductor. They also apply to the whole substance of a solid conductor, and to the whole space inclosed within the outer surface of a hollow conductor. Whenever a conductor is in electrical equilibrium, it has the same potential throughout the whole of its substance, and also through any completely inclosed hollows which it may contain.

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[1] DEFINITION.—There is electrical force at a point in the air, if an electrified particle placed there would experience force tending to move it in virtue of electrical attraction or repulsion. There is electrical force at a point in a conductor, when electricity flows through the point. A conductor is said to be in electrical equilibrium, when there is no electrical force at any part of it; in other words, when it is completely free from currents of electricity.

When a conductor is not in electrical equilibrium, currents set in, tending to restore equilibrium; and the direction of such currents is always from places of higher to places of lower potential. In like manner, when a small positively electrified body experiences electrical force tending to move it, the direction of this force is from higher to lower potential.

When flow of electricity is compared with flow of heat, potential is the analogue of temperature. Heat flows from places of higher to places of lower temperature.

The precise direction of the force exerted upon a positively electrified particle (or upon an element of positive electricity), when brought to a place where potential has not a constant value from point to point, is the direction in which potential diminishes most rapidly. A negatively electrified particle (or an element of negative electricity) will be urged in the opposite direction, which is the direction in which potential increases most rapidly. We here use the words *increase* and *decrease* in the algebraical sense.

445c. Line of Force.—The direction thus defined (especially by reference to the force on the *positive* particle) is called *the direction of resultant electrical force* at the point where the particle is placed. If a line be traced such that every small portion of it (small enough to be regarded as straight) is the direction of resultant electrical force at the points which lie upon it, it is called a *line of force;* in other words, a line of force is *a line whose tangent at any point is the direction of resultant electrical force at that point.* We may express this briefly by saying that lines of electrical force are *the lines along which resultant electrical force acts.*

It is evident that lines of force cannot cut one another, since we cannot have two different directions of resultant force at a point.

445d. Intensity of Force is Equal to Rate of Variation of Potential.—The intensity of resultant force at a point is equal to the rate at which potential diminishes in the direction in which the diminution is most rapid, namely, along a line of force at the point. Let V denote the potential at the point, and $V - \delta V$ the potential at a neighbouring point on the same line of force, at a distance δs from the first point; then $\frac{\delta V}{\delta s}$ is the intensity of force at either point, or, more strictly, is the average intensity along the short line δs, and the direction of the force (for a positive particle) is from the first point towards the second.

A similar proposition applies to two neighbouring points not situated on the same line of force; the component force, in the direction of a line joining them, is equal to $\frac{\delta V}{\delta x}$, where δx denotes the length of the joining line, and δV the difference of the potentials of the two points. This proposition is usually expressed by saying that *the rate of variation of potential in any direction is equal to the component force in that direction.*

445 E. Relation between Potential and Work.—The work done by or against electrical force in carrying a unit of electricity through this distance δx is the product of force by distance, and is therefore simply δV. More generally, the work done by or against electrical force in carrying a unit of electricity from one point to another, is equal to the difference of potentials of the two points; and the work done in carrying any quantity of electricity is the product of this quantity by the difference of potentials.

An analogy is thus suggested between different potentials and different *levels.* Positive electricity tends to run down from higher to lower potential, and, when it does so run down, there is a loss of *potential energy* equal to the *product of the quantity* which runs down, *and the difference of potential* through which it runs down. When the quantity which runs down is unity, the loss of potential energy is equal to the loss of potential. It is usual to assume, as the zero of potential, the potential of the earth at the place of observation; but this assumption is not rigorously consistent with itself, since the existence of earth-currents demonstrates that different potentials may exist at different parts of the earth. Electrical potential is rigorously zero at places infinitely distant from all electricity.

445 F. Equipotential Surfaces.—An equipotential surface is a surface over the whole of which there is the same value of potential. It is obvious, from the latter part of § 445 D, that there is no tangential force at any point of such a surface. The direction of resultant force is everywhere normal to the surface, or *equipotential surfaces everywhere cut lines of force at right angles.* An equipotential surface is the analogue of a *level surface.* If two equipotential surfaces are given, their potentials being V_1 and V_2, the work done in carrying a unit of electricity from any point of the one to any point of the other, is constant, and equal to the difference of V_1 and V_2.

If we consider two equipotential surfaces very near to one another, so that the portions which they intercept on the lines of force may be regarded as straight, the intensity of force at different points of the intermediate space will vary inversely as the distance between the two equipotential surfaces; for, when equal amounts of work are done in travelling unequal distances, the forces must be inversely as the distances.

445G. Tubes of Force.—If we conceive a narrow tube bounded on all sides by lines of force, and call it a *tube of force*, we can lay down the following remarkable rules[1] for the comparison of the forces which exist at different points in its length. (1) *In any portion of a tube of force not containing electricity, the intensity of force varies inversely as the cross-section of the tube*, or the product of *intensity of force by section of tube*, is constant.[2] (2) *When a tube of force cuts through electricity, this product changes, from one side of this electricity to the other, by the amount* $4\pi q$, where q denotes the quantity of the electricity inclosed by the tube.

The following are particular cases of (1):—

When the electricity to which the force is due is collected in a point, the lines of force are straight, the tubes of force are cones (in the most general sense), and the law of force becomes the law of inverse squares, since the section of a cone varies as the square of the distance from the vertex. These results also apply to the case of electricity uniformly distributed over the surface of a sphere, the common vertex of the cones being now at the centre of the sphere.

When the electricity consists of the charges of two oppositely electrified parallel plates, whose length and breadth exceed the distance between them (the plates being conductors, and placed opposite to each other), the lines of force between their central portions are sensibly straight and parallel, the tubes of force are therefore cylinders (in the most general sense), and the force is constant, being equal to the difference of the potentials of the plates divided by the distance between them. The same thing holds if, instead of being oppositely electrified, the plates are similarly electrified, but not to the same potential.

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[1] For the proof of these rules, as mathematical deductions from the law of inverse squares, see Thomson and Tait's *Natural Philosophy*, §§ 490, 492.

[2] This is obviously analogous to the law which applies to the comparison of the velocities of a liquid in different parts of a tube through which it flows, since the product of area by velocity is the volume of liquid which flows past any section in unit time. The tube may be an imaginary one, bounded by lines of flow in a large body of liquid flowing steadily. Lines of flow are thus the analogues of lines of force.

445 H. Force Proportional to Number of Tubes which cut Unit Area.—The cross-sections of tubes of force are portions of equipotential surfaces. If one equipotential surface be divided into portions, such that the product of *area by force-intensity* shall be the same for all, then, if all neighbouring space not containing electricity be cut up into tubes, springing from these portions as their respective bases, the product of any cross-section of any one of these tubes by the force-intensity over it will be constant. The force-intensities at any points in this space are therefore inversely as the cross-sections of the tubes at these points, or are directly as the number of tubes per unit area of equipotential surfaces at the points.

445 I. Force just Outside an Electrified Conductor.—Since there is no force in the interior of a conductor, the lines and tubes of force become indeterminate; but proposition (2) of § 445 G can be shown to hold when we give them any shape not discontinuous. Let ρ denote the electric density at a point on the surface, and a a small area around this point, which area we shall regard as a section of a tube of force cutting through the surface. Let F denote intensity of force just outside the surface opposite this point, then, since the intensity inside is zero, we have

$$\mathrm{F}\,a = 4\,\pi\,q = 4\,\pi\,\rho\,a \quad \therefore \mathrm{F} = 4\,\pi\,\rho;$$

that is, *the intensity of force just outside any part of the surface of a charged conductor, is equal to the product of* 4 π *into the density at the nearest part of the surface.*

445 J. Relation of Induction to Lines and Tubes of Force.—Lines of force are also the lines along which induction takes place. On Faraday's theory of induction by contiguous particles, the line of poles, for any particle, is coincident with the line of force which passes through the particle. Apart from all theory, it is matter of fact that *a tube of force extending from an influencing to an influenced conductor, and not containing any electricity in the interval between, has equal quantities of electricity on its two ends, these quantities being of opposite sign.* This equality follows at once from § 445 G (2), if we consider the tube as penetrating the two conductors; for the product of force by section, which is constant for the portion of the tube in air, is zero in both conductors; and the quantity of electricity on *either* end of the tube must be the quotient of this constant product by 4π. In connection with this reasoning, it is to be remarked that the surface of a conductor is an equipotential surface, and is cut at right angles by lines of force.

In Faraday's ice-pail experiment, a tube of force springing from the upper side of the charged ball, and of such small section at its origin as to inclose only an insensible fraction of the charge of the ball, opens out so fast, as it advances, that it fills the whole opening at the top of the pail.

In every case of induction, *the total quantities of inducing and induced electricity are equal, and of opposite sign.*

When the inducing electricity resides in or upon a non-conductor, for example on the surface of a glass rod, or in the substance of a mass of air, the quantity of electricity induced on the base of a tube of force is equal and opposite to the quantity contained within the tube. In the simplest case, all the tubes will have a common apex, which will be a point of maximum or minimum potential.

445K. Potential defined as $\Sigma\frac{q}{r}$.

The resultant potential at a point, due to several different quantities of electricity, is the algebraical sum of the potentials due to the different quantities separately considered. This would follow at once from the relation above indicated as existing between potential and work.

If the unit of quantity of electricity be defined as that quantity which, at unit distance, produces unit intensity of force, it can be shown[1] that the whole work done by or against the force of an element q, in bringing a unit of electricity from infinite distance to a point at a distance r from the element, is $\frac{q}{r}$. This expression therefore denotes the potential due to q at the distance r, if we adopt the very natural convention that the potential at infinite distance shall be reckoned zero.

The resultant potential at a point, due to the presence of any quantity of electricity distributed in any way, is to be computed by dividing the electricity into elements, each occupying so little space that all parts of it may be regarded as at the same distance from the point, and summing all the quotients $\frac{q}{r}$. The distances denoted by r are essentially positive. If the electricity is not all of one sign, some of the quotients $\frac{q}{r}$ will be positive, and others negative, and their algebraical sum is to be taken.

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[1] See *Thomson and Tait*, § 491, first paragraph.

445 L. Application to Sphere.—In the case of a charged conducting sphere, all the elements q are equally distant from the centre of the sphere, and the sum of the quotients $\frac{q}{r}$, when we are computing the potential at the centre, will be $\frac{Q}{R}$, Q denoting the charge, and R the radius of the sphere. But the potential is the same at all points in a conductor. $\frac{Q}{R}$ is therefore the potential of a sphere of radius R, with charge Q, when uninfluenced by any other electricity than its own.

445 M. Capacity.—The electrical capacity of a conductor is *the quantity of electricity required to charge it to unit potential*, when it is not influenced by any other electricity besides its own charge and the electricity which this induces in neighbouring conductors. Or, since, in these circumstances, potential varies directly as charge, capacity may be defined as the *quotient of charge by potential.* Let C denote capacity, V potential, and Q charge, then we have

$$C = \frac{Q}{V} \quad ; \quad V = \frac{Q}{C} \quad ; \quad Q = VC.$$

But we have seen that for a sphere of radius R, at a distance from other conductors or charged bodies, $V = \frac{Q}{R}$. Hence $C = R$; that is, the *capacity of a sphere is numerically equal to its radius.*

This is a particular instance of the general proposition that the capacities of similar conductors are as their linear dimensions; which may be proved as follows:—

Let the linear dimensions of two similar conductors be as $1 : n$. Divide their surfaces *similarly* into very small elements, which will of course be equal in number. Then the areas of corresponding elements will be as $1 : n^2$, and, if the electrical densities at corresponding points be as $1 : x$, the charges on corresponding elements are as $1 : n^2x$. The potential at any selected point of either conductor is the sum of such terms as $\frac{q}{r}$ (§ 445 K). Selecting the corresponding point in the other conductor, and comparing potentials, the values of q are as $1 : n^2x$, and the values of r are as $1 : n$; therefore the values of $\frac{q}{r}$ are as $1 : nx$. Hence the potentials of the two conductors are as $1 : nx$. If they are equal, we have $nx = 1$, and therefore $n^2x = n$; that is, the charges on corresponding elements, and therefore also on the whole surfaces, are as $1 : n$.

We shall see, in the chapter on Condensers, that the capacity of a conductor may be greatly increased by bringing it near to another conductor connected with the earth.

445 N. Connection between Potential and Induced Distribution.—In the circumstances represented in Fig. 336 (§ 412), if we suppose the influencing body C to be positively charged, the potential due to this charge will be algebraically greater at the near end A of the influenced conductor than at the remote end B. The induced electricity on AB must be so distributed as to balance this difference, in fact the potential due to this induced electricity is negative at A and positive at B. All cases of induced electricity upon conductors fall under the rule that *the potential at all parts of a conductor must be the same, and hence, wherever the potential due to the influencing electricity is algebraically greatest, the potential due to the electricity on the influenced conductor must be algebraically least.*

As there can be no force in the interior of a conductor, the force at any point in the interior, due to the influencing electricity, must be equal and opposite to the force due to the electricity on the surface of the conductor. This holds, whether the conductor be solid or hollow. A hollow conductor thus completely screens from external electrical forces all bodies placed in its interior.

445 O. Electrical Images.—If a very large plane sheet of conducting material be connected with the earth, and an electrified body be placed in front of it near its middle, the plate will completely screen all bodies behind it from the force due to the electrified body. The induced electricity on the plate therefore exerts, at all points behind the plate, a force equal and opposite to that of the electrified body, or, what is the same thing, a force identical with that which the electrified body would exert if its electricity were reversed in sign. But electricity distributed over a plane surface must act symmetrically towards both sides. Hence the force which the induced electricity exerts in front, is identical with that which would be exerted by a body precisely similar to the given electrical body, symmetrically placed behind the plane, and charged with the opposite electricity. The total force at any point in front of the plane is the resultant of the force due to the given electrified body, and the force due to this imaginary image. The name and the idea of *electrical images*, of which this is one of the simplest examples, are due to Sir W. Thomson.

CHAPTER XI.

ELECTRICAL CONDENSERS.

445 P. Condensers.—The process called *condensation of electricity* consists in increasing the capacity of a conductor by bringing near it another conductor connected with the earth. The two conductors are usually thin plates or sheets of metal, placed parallel to one another, with a larger plate of non-conducting material between them.

Let A and B (Fig. 379) be the two conducting plates, of which A, called the *collecting plate*, is connected with the conductor of the machine, and B, called the *condensing plate*, with the earth; and let C be the non-conducting plate (or dielectric) which separates them. Then, if the machine has been turned until the limit of charge is attained, the surface of B which faces towards A is covered with negative electricity, drawn from the earth, and held by the attraction of the positive electricity of A; and, conversely, the surface of A which faces towards B, is covered with positive electricity, held there by the attraction of the negative of B, in addition to the charge which would reside upon it if the conductor were at the existing potential, and B and C were absent. In fact, the electrical density on the face of A, as well as the whole charge of A, would, in this latter case, be almost inappreciable, in comparison with those which exist in the actual circumstances. By condensation of electricity, then, we are to understand *increase*—usually enormous increase—

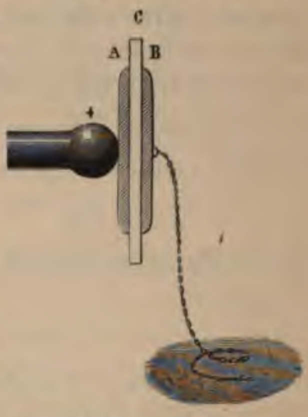

Fig. 379.—Theoretical Condenser.

of electrical density on a given surface, attained without increase of potential. If two conducting plates, in other respects alike, but one with, and the other without a condensing plate, be connected by a wire, and the whole system be electrified, the two plates will have the same potential, but nearly the whole of the charge will reside upon the face of that which is accompanied by a condensing plate.

445 Q. Calculation of Capacity of Condenser.—The lines of force between the two plates A and B are everywhere sensibly straight and perpendicular to the plates, with the exception of a very small space round the edge, which may be neglected. The tubes of force (§ 445 G) are therefore cylinders, and the intensity of force is constant at all parts of their length. Also, since the potential of the plate B is zero, if we take V to denote the potential of the plate A, which is the same as the potential of the conductor, and t to denote the thickness of the intervening plate C, the rate at which potential varies along a line of force is $\frac{V}{t}$, which is therefore (§ 445 D) the expression for the force at any point between the plates A, B. The whole space between the plates may be regarded as one cylindrical tube of force of cross-section S equal to the area of either plate, the two ends of the tube being the inner faces of the plates. The quantities of electricity $\pm$ Q residing on these faces are therefore equal, but of opposite sign (§ 445 J); and as the force changes from nothing to $\frac{V}{t}$ in passing from one side to the other of the electricity which resides on either of these surfaces, we have (§ 445 G)

$$\frac{V}{t}.S = 4\pi Q.$$

Hence the capacity of the plate A, being, by definition, equal to $\frac{Q}{V}$, is equal to

$$\frac{S}{4\pi t}.$$

We should, however, explain that, if the intervening plate C is a solid or liquid, we are to understand by t not the simple thickness, but the thickness reduced to an equivalent of air, in a sense which will be explained further on (§ 453). This reduced thickness is, in the case of glass, about half the actual thickness.

If s denote an element of area of A, and q the charge residing upon it, it is evident, from considering the tube of force which has s for one of its ends, that

$$\frac{V}{t}.s = 4\pi q;$$

and the electric density $\frac{q}{s}$ on the element is equal to $\frac{V}{4\pi t}$, which is constant over the whole face of the plate.

To give a rough idea of the increase of capacity obtained by the employment of a condensing plate, let us compare the capacity of a circular disc of 10 inches diameter, accompanied by a condensing plate at a reduced distance of $\frac{1}{20}$ of an inch, with the capacity of a globe of the same diameter as the disc. The capacity of the globe is equal to its radius, and may therefore be denoted by 5. The capacity of the disc is $\frac{25\pi}{4\pi \times \frac{1}{20}} = 125$, or 25 times the capacity of the globe. It is, in fact, the same as the capacity of a globe 250 inches (or 20 ft. 10 in.) in diameter.

446. Discharge of Condenser.—If, by means of a jointed brass discharger (Fig. 380) with knobs M N at the ends, and with glass handles, we put the two plates A and B in communication, a brilliant spark is obtained, resulting from the combination of the positive charge of A with the negative of B, and the condenser is discharged. When the quantity of electricity is small, the glass handles are unnecessary, and the simpler apparatus represented in Fig. 381 may be employed, consisting simply of two brass rods jointed together, and with knobs at their ends, care being taken to touch the plate B, which is in communication with the earth, before the other. The operator will then experience no shock, as the electricity passes in preference through the brass rods, which are much better conductors than the human body. If, however, the operator discharges the

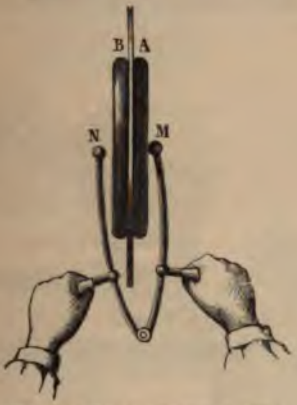

Fig. 380.—Discharge of Condenser.

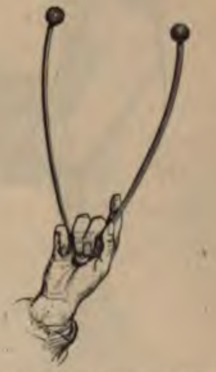

Fig. 381.—Discharger without Handles.

condenser with his hands by touching first the plate B, and then also the plate A, the whole discharge takes place through his arms and chest, and he experiences a severe shock. If he simply touches the plate A, while B remains connected with the earth by a chain, as in Fig. 379, he receives a shock, but less violent than before, because the discharge has now to pass through external bodies which consume a portion of its energy. If, instead of a chain, B is connected with the earth by the hand of an assistant touching it, he too will receive a shock when the operator touches A.

447. Discovery of Cuneus.—The invention of the Leyden jar was brought about by a shock accidentally obtained. Some time in the year 1746, Cuneus, a pupil of Muschenbroeck, an eminent philosopher of Leyden, wishing to electrify water, employed for this purpose a wide-mouthed flask, which he held in his hand, while a chain from the conductor of the machine dipped in the water (Fig. 382). When the experiment had been going on for some time, he wished to disconnect the water from the machine, and for this purpose was about to lift out the chain; but, on touching the chain, he experienced a shock, which gave him the utmost consternation, and made him let

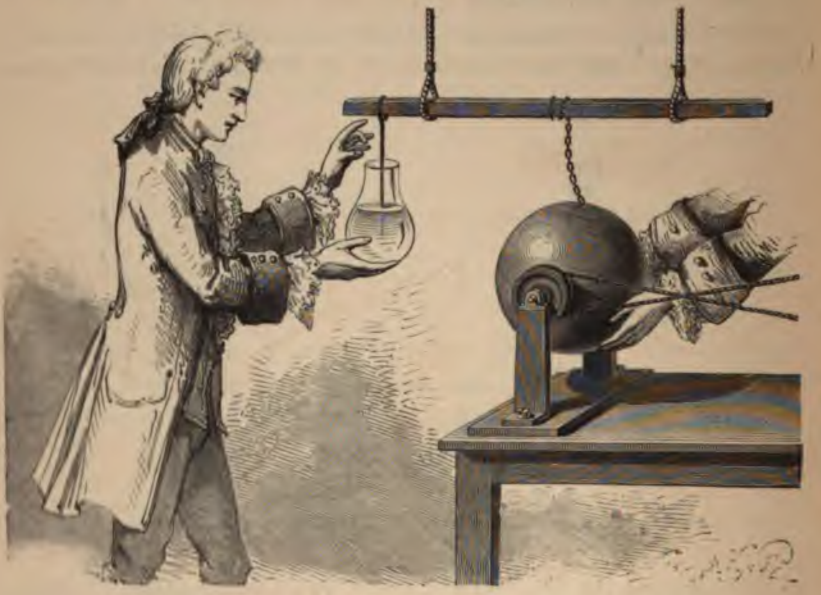

Fig. 382.—Experiment of Cuneus.

fall the flask. He took two days to recover himself, and wrote to Réaumur that he would not expose himself to a second shock for the crown of France. The news of this extraordinary experiment spread over Europe with the rapidity of lightning, and it was eagerly repeated everywhere. Improvements were soon introduced in the arrangement of the flask and its contents, until it took the present form of the *Leyden Phial* or *Leyden Jar*. It is easy to see that the effect obtained by Cuneus depended on condensation of electricity, the water in the vessel serving as the collecting plate, the hand as condensing plate, and the vessel itself as the dielectric. When he touched the chain, the two oppositely charged conductors were put in communication through the operator's body, and he received a shock.

448. Leyden Jar.—The Leyden jar, as now usually constructed, consists of a glass jar coated, both inside and out, with tin-foil, for about four-fifths of its height. The mouth is closed by a cork, through which passes a metallic rod, terminating above in a knob,

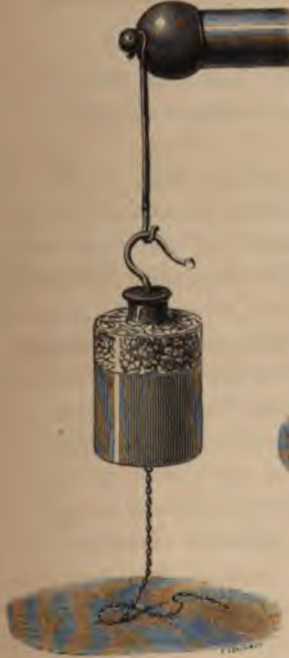

Fig. 383.—Leyden Jar.

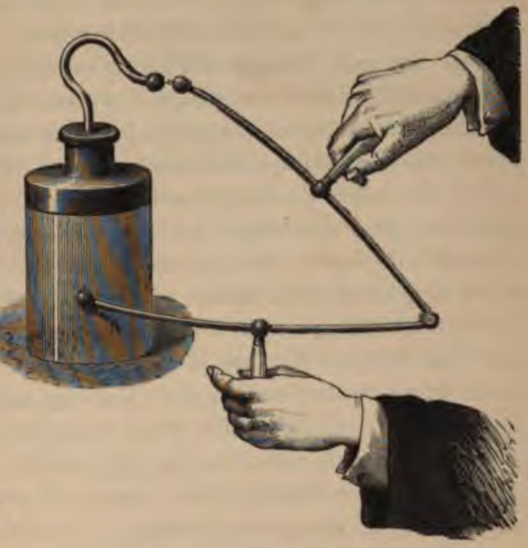

Fig. 384.—Discharge of Leyden Jar.

and connected below with the inner coating, either by a chain depending from it, or by pieces of metallic foil with which the jar is filled. The interior of the jar must be thoroughly dry before it is closed, and the cork and neck are usually covered with sealing-wax, and shellac varnish, which is less hygroscopic than glass. The Leyden jar is obviously a condenser, its two coatings of tin-foil performing the parts of a collecting plate and a condensing plate. If the inner coating is connected with the electrical machine, and the outer coating with the earth, the former acquires a positive, and the latter a negative charge. On connecting them by a discharger, as in Fig. 384, a spark is obtained, whose power depends on the potential of the inner coating, and on its electrical capacity. If these be denoted respectively by V and C, and if Q denote the quantity of electricity residing on either coating, the amount of electrical energy which runs down and undergoes transformation when the jar is discharged, is $QV = CV^2 = \frac{Q^2}{C}$.

The quantities Q, V, C, which are, properly speaking, the charge, potential, and capacity of the *inner coating*, are usually called the charge, potential, and capacity of the jar.

449. Residual Charge.—When a Leyden jar has been discharged by connecting its two coatings, if we wait a short time we can obtain another but much smaller spark by again connecting them, and other sparks may sometimes be obtained after further intervals. These are called secondary discharges, and the electricity which thus remains after the first discharge is called the *residual charge.* Faraday's experiments leave little room for doubt that they depend mainly upon a gradual penetration of electricity from both sides into the substance of the glass, to a very small depth, but sufficient to prevent the electricity which has so entered from at once escaping to the earth when connection is made. Faraday appeals to this phenomenon as strongly confirming his view that the difference between conductors and non-conductors is only one of degree, this penetration being only an extremely slow process of conduction. A small part of the residual charge also consists of electricity spread over the surface of the glass beyond the edges of the coatings.

The whole charge of the outer coating, and all except an insignificant portion of the charge of the inner coating, resides on the side of the foil which is in contact with the glass, or, more probably, on the surfaces of the glass itself, the mutual attraction of the two opposite electricities causing them to approach as near to each other as the glass will permit. This is illustrated by Franklin's experiment of the *jar with movable coatings* (Fig. 385). The jar is charged in the ordinary way, and placed on an insulating stand. The inner coating is then lifted out by a glass hook, and touched with the hand to discharge it of any electricity which it may retain. The glass is then lifted out, and the outer coating also discharged. The jar is then put together again, and is found to give nearly as strong a spark as it would have given originally.

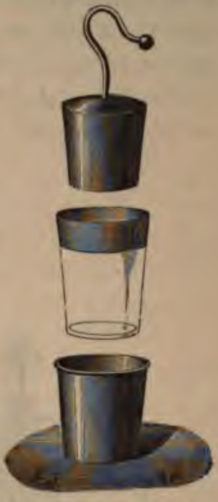
Fig. 385.—Jar with Movable Coatings.

450. Discharge by Alternate Contacts.—Instead of discharging a Leyden jar at once by connecting its two coatings, we may gradually discharge it by alternate contacts. To do this, we must set it on an insulating stand (or otherwise insulate both coatings from the earth), and then touch the two coatings alternately. At every contact a small spark will be drawn. The coating last touched has always rather less electricity upon it than the other, but the difference is an exceedingly small fraction of the whole charge, and, after a great number of sparks have been drawn by these alternate contacts, we may still obtain a powerful discharge by connecting the two coatings.

The quantities of electricity thus alternately discharged from the two coatings form two decreasing geometric series, one for each coating. In fact, if m and m' be two proper fractions such that, when the outer coating is connected with the earth, the ratio of its charge to that of the inner is $-m$; and, when the inner coating is connected with the earth, the ratio of its charge to that of the outer is $-m'$, we have the following series of values:—

	On inner coating.		On outer coating.
Original charges, ...	$+ Q$	...	$- m Q$
After 1st contact, ...	$+ m'm Q$	...	$- m Q$
2d „	$+ m'm Q$	...	$- m'm^2 Q$
3d „	$+ m'^2 m^2 Q$	...	$- m'm^2 Q$
	&c.		&c.

The quantities discharged from the inner coating are, successively $(1-m'm)$ Q , $m'm$ $(1-m'm)$ Q , m'^2m^2 $(1-m'm)$ Q, &c.; and the quantities successively discharged from the outer, neglecting sign, are, $m\,(1-m'm)\,Q$, $m'm^2\,(1-m'm)\,Q$, $m'^2m^3\,(1-m'm)\,Q$, &c.

The quantity $(1-m'm)\,Q$ discharged at the first contact, represents that portion of the charge[1] which is not due to condensation; so that the actual capacity of the Leyden jar is to the capacity of the inner coating if left to itself as $1 : 1-m'm$.

The discharge by alternate contacts can be effected by means of a carrier suspended between two bells, as in Fig. 386. The rod from the inner coating terminates in a bell, and the outer coating is connected, by means of an arm of tin, with another bell supported on a metallic column. An insulated metallic ball is suspended between the two. This is first attracted by the positive bell. Then, being repelled by this and attracted by the other, it carries its charge of positive electricity to the negative bell, and receives a charge of negative, which it carries to the positive bell, and so on alternately. The whole apparatus stands upon an insulating support. It is not, however, necessary that the carrier should be insulated from the earth, but it must be insulated from both coatings.

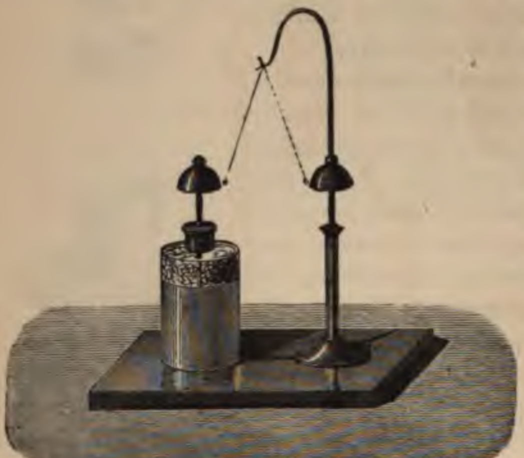

Fig. 386.—Alternate Discharge.

451. Condensing Power.—By the condensing power of a given arrangement is meant the ratio in which the capacity of the collecting plate is increased by the presence of the condensing plate, which ratio, as we have seen in last section, is equal to the fraction $\frac{1}{1-m'm}$. Riess has investigated its amount experimentally under varying conditions, by means of the apparatus represented in Fig. 387, which is a modification of the condenser of Æpinus. It consists of two metallic plates A and B, supported on glass pillars, and travelling on a rail, so that they can be adjusted at different distances. Between them is a large glass plate C. A is charged from the machine, B being at the same time touched to connect it with the ground. The electrical density on the anterior face of A was observed by means of Coulomb's proof-plane and torsion-balance. Riess' experiments are completely in agreement with the theory laid down in the preceding sections of this chapter; for example, he found, among other results, that the condensing power was independent of the absolute charge, and that it varied nearly in the inverse ratio of the distance.

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[1] This portion of the original charge is said to be *free*, and the remaining portion to be *bound*, *dissimulated*, or *latent*. These terms are applicable to all cases of condensation.

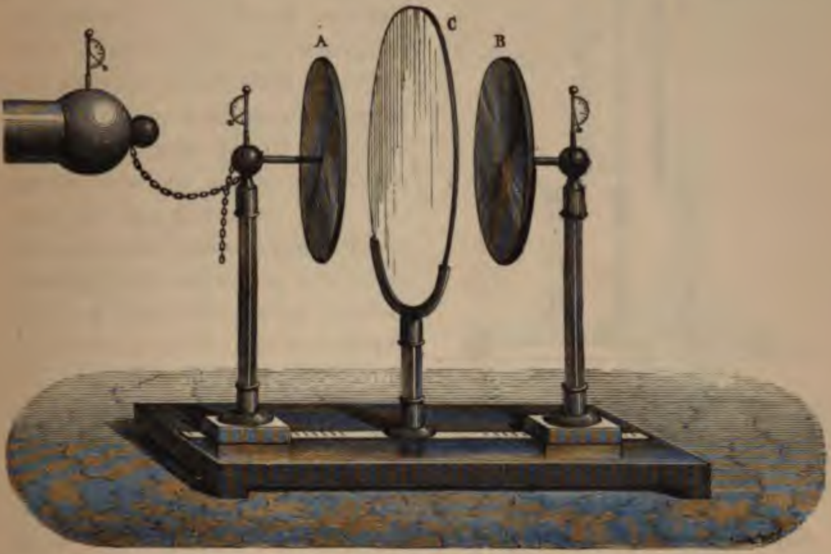

Fig. 387.—Condenser of Æpinus.

453. Influence of the Dielectric.—Faraday discovered that the amount of condensation obtained in given positions of the two conducting plates, depended upon the material of the *intervening non-conductor* or *dielectric.* The annexed figure (Fig. 388) represents a modification of one of Faraday's experiments. A is an insulated metallic disc, with a charge, which we will suppose to be positive. B and C are two other insulated metallic discs at equal distances from A, each having a small electric pendulum suspended at its back. Let B and C be touched with the hand; they will become negatively electrified by induction, but their negative electricity will reside only on their sides which face towards A, and the pendulums will hang vertically. If, while matters are in this condition, we move B nearer to A, we shall see both the pendulums diverge, and, on testing, we shall find that the pendulum B diverges with positive, and C with negative electricity. The reason is obvious. The approach of B to A causes increased induction between them, so that more negative is drawn to the face of B, and positive is driven to its back; at the same time the symmetrical distribution of electricity on A is disturbed, a portion being accumulated on the side next B at the expense of the side next C. The inductive action of A upon C is thus diminished, and a portion of the negative charge of C is left free to spread itself over the back, and affect the pith-ball.

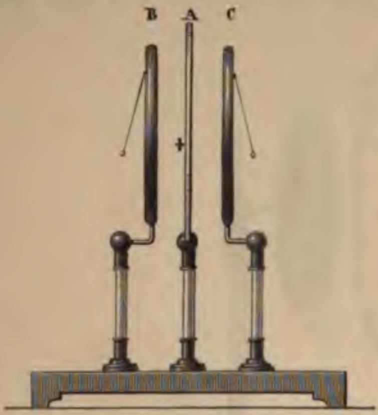

Fig. 388.—Change of Distance.

If, while the discs are in their initial position, B and C being equidistant from A, and the pendulums vertical, we interpose between B and A a plate of sulphur, shellac, or any other good insulator, the same effect will be produced as if B had been brought nearer to A. We see, then, that the insulating plate of a condensing arrangement serves not only to prevent discharge, but also to increase the inductive action and consequent condensation, as compared with a layer of air of the same thickness; inductive action through a plate of sulphur or shellac of given thickness, is the same as through a thinner plate of air. The numbers in the subjoined table denote the thickness of each material which is equivalent to unit thickness of air. For example, the mutual induction through 2·24 inches of sulphur is the same as through 1 inch of air. These numbers are called

SPECIFIC INDUCTIVE CAPACITIES.

Air or any gas,	1·00	Pitch,	1·80
Spermaceti,	1·45	Wax,	1·86
Glass,	1·76	Shellac,	2·00
Resin,	1·77	Sulphur,	2·24

The quotient of the actual thickness of the plate by the specific inductive capacity of its material may appropriately be called the *thickness reduced to its equivalent of air*, or simply the *reduced thickness*.

454. Faraday's Determinations.—Faraday, to whom the name and discovery of specific inductive capacity are due, operated by comparing the capacities of condensers, alike in all other respects, but differing in the materials employed as dielectrics. One of his condensers is represented in Fig. 389. It is a kind of Leyden jar, containing a metallic sphere A, attached to the rod M, and forming with it the inner conductor. The outer conductor consists of the hollow sphere B, divided into two hemispheres which can be detached from each other. The interval between the outer and inner conductor can be filled, either with a cake of solid non-conducting material, or with gas, which can be introduced by means of the cock R. The method of observation and reduction will be best understood from an example.

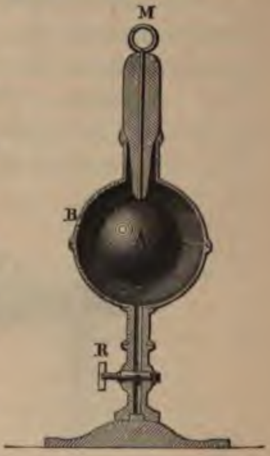

Fig. 389.—Apparatus for Specific Inductive Capacity.

The interval being occupied by air, the apparatus was charged, and a carrier-ball, having been made to touch the summit of the knob M, was introduced into a Coulomb's torsion-balance, and found to be charged with a quantity of electricity represented by 250° of torsion. When the second apparatus was precisely similar to the first, it was found that, on contact of the two knobs, the charge divided itself equally, and the carrier-ball, if applied to either knob, took a charge represented very nearly by 125°.

The conditions were then changed in the following way. The first jar still containing air, the interval between the two conductors in the second was filled with shellac. It was then found that the air-jar, being charged to 290°, was reduced, by contact of its knob with that of the shellac-jar, to 114°, thus losing 176°. If no allowance be made for dissipation, the capacities of the air-jar and shellac-air would therefore be as 114 : 176, or as 1 : 1·54, and the specific inductive capacity of shellac would be 1·54.

455. Polarization of the Dielectric.—As the interposed non-conductor, or dielectric, modifies the mutual action of the two electricities which it separates, and does not play the mere passive part which was attributed to it before Faraday's experiments, it is natural to conclude that the dielectric must itself experience a peculiar modification. According to Faraday, this modification consists in a polarization of its particles, which act inductively upon each other along the lines of force, and have each a positive and a negative side, the positive side of each facing the negative side of the next. This polarization is capable of being sustained for a great length of time in good non-conductors; but in good conductors it instantly leads to discharge between successive particles, and the opposite electricities appear only at the two surfaces.

The polarization of dielectrics is clearly shown in the following experiment. In a glass vessel (Fig. 390) is placed oil of turpentine, containing filaments of silk 2 or 3 millimetres long. Two metallic rods, A, B, each terminating within in a point, are connected, one with the ground, and the other with an electric machine. On working the machine, the little filaments are seen to arrange themselves in a line between the points, and, on endeavouring to break the line with a glass rod, it will be found that they return to this position with considerable pertinacity. On stopping the machine, they immediately fall to the bottom.

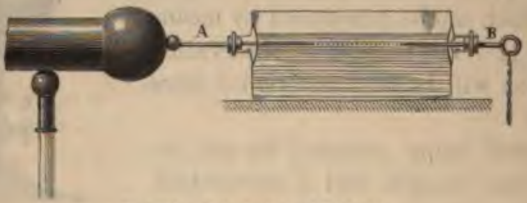

Fig. 390.—Polarization of Dielectric.

An experiment of Matteucci's demonstrates this polarization still more directly. A number of thin plates of mica are pressed strongly together between two metallic plates. One of the metallic plates is charged, while the other is connected with the ground; and, on removing the metallic plates by insulating handles, it is found that all the mica plates are polarized, the face turned towards the positive metal plate being covered with positive electricity, and the other face with negative.

459. Limit to Thinness of Interposed Plate.—We have seen (§ 445Q) that the capacity of a condenser varies inversely as the distance between the collecting and the condensing plate. But if this distance is very small, the resistance of the interposed dielectric (which varies directly as its thickness) may be insufficient to prevent discharge, and it will not be practicable to establish a great difference of potential between the two plates. We may practically distinguish two sorts of condensers, one sort having a very thin dielectric and very great condensing power, but only capable of being charged to feeble[1] potential; the other having a dielectric thick enough to resist the highest tensions attainable by the electrical machine. The Leyden jar comes under the second category. The first includes the electrophorus (except in so far as its action is aided by the metallic sole), and the condenser of Volta's electroscope.

460. Volta's Condensing Electroscope.—This instrument, which has rendered very important services to the science of electricity, differs from the simple gold-leaf electroscope previously described (§ 415), in having at its top two metal plates, of which the lower one is connected with the gold-leaves, and is covered on its upper face with insulating varnish, while the upper is varnished on its lower face, and furnished with a glass handle. These two plates constitute the condenser. In using the instrument, one of the two plates (it matters not which) is charged by means of the body to be tested, while the other is connected with the earth. They thus receive opposite and sensibly equal charges. The upper plate is then lifted off, and the higher it is raised the wider do the gold-leaves diverge. The separation of the plates diminishes the capacity, and strengthens the potential of both, one becoming more strongly positive, and the other more strongly negative. This involves increase of potential energy, which is represented by the amount of work done against electrical attrac-

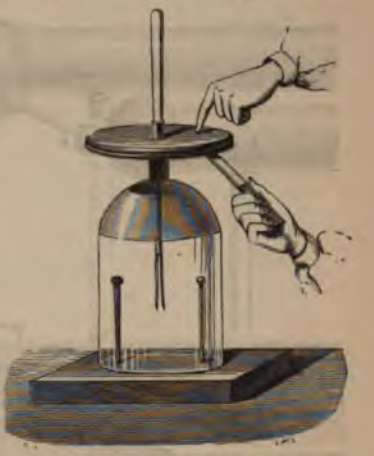

Fig. 391.—Condensing Electroscope.

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[1] *Strong* potential is potential differing very much from zero either positively or negatively. *Feeble* potential is potential not differing much from zero. *Tension* is measured by difference of potential; and when the earth is one of the terms of the comparison, tension becomes identical with potential.

tion in separating the plates. No increase in quantity of electricity is produced by the separation; hence the instrument is chiefly serviceable in detecting the presence of electricity which is available in large quantity but at weak potential. The glass handle of the upper plate is by no means essential, as it is only necessary that the lower plate should be insulated. The charge may be given by induction; in which case one plate must be connected with the earth while the inducing body is held near it, and the other plate must be kept connected with the earth while the influencing body is withdrawn. The plates will then be left charged with opposite electricities, that which was more remote from the influencing body having acquired a charge similar to that of the body. For inductive charges, however, the condensing arrangement serves no useful purpose, beyond enabling the electroscope to retain its charge for a longer time, the effect finally obtained on separating the plates being no greater than would have been obtained by employing only the lower plate.

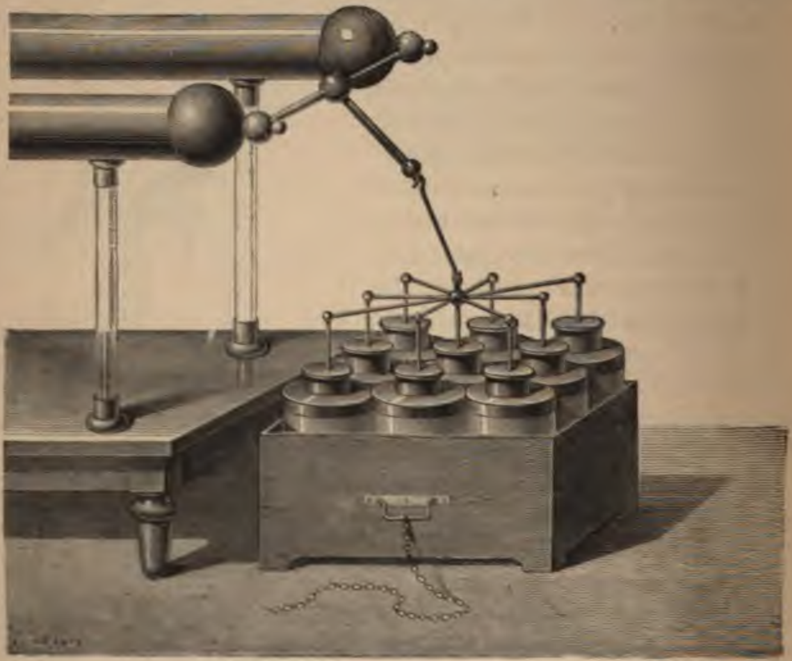

Fig. 392.—Battery of Leyden Jars.

461. Leyden Battery.—The Leyden battery consists of a number of

Leyden jars, placed in compartments of a box lined with tin-foil, which serves to establish good connection between their outer coatings, while their inner coatings are connected by brass rods. It is advisable that the outer coatings should have very free communication with the earth. For this purpose a metallic handle, which is in metallic communication with the lining of the box, should be connected, by means of a chain, with the gas or water pipes of the building.

The capacity of a Leyden battery is the sum of the capacities of the jars which compose it. The charge is given in the ordinary way, by connecting the inner coatings with the conductor of the machine. In bad weather this is usually a very difficult operation, on account

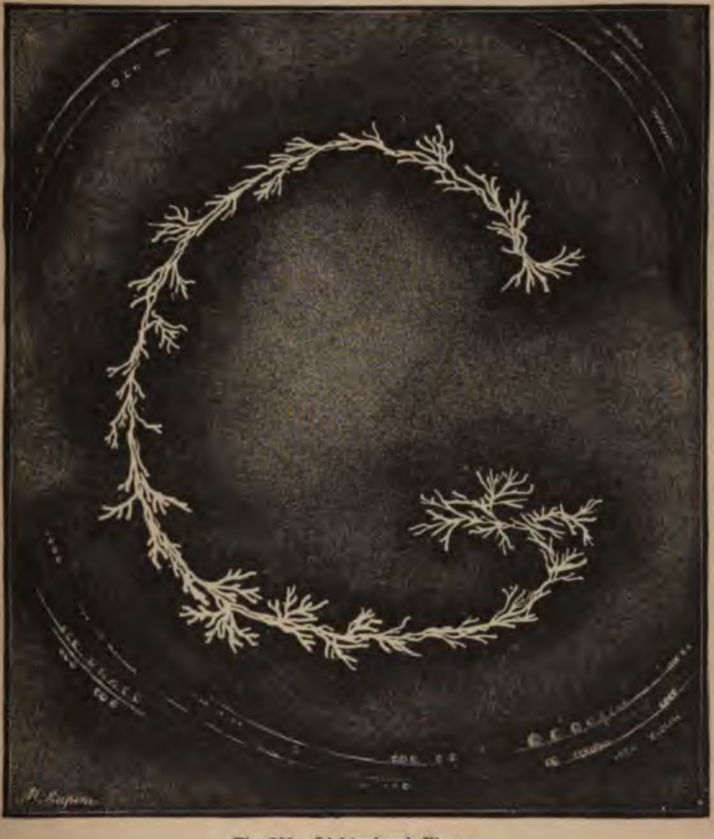

Fig. 393.—Lichtenberg's Figures

of the large quantity of electricity required for a full charge. and the large surface from which dissipation goes on.

Holtz's machine can be very advantageously employed for charging a battery, one of its poles being connected with the inner, and the other with the outer coatings. In dry weather it gives the charge with surprising quickness.

462. Lichtenberg's Figures.—An interesting experiment devised by Lichtenberg serves to illustrate the difference between the physical properties of positive and negative electricity.

A Leyden jar is charged, and the operator, holding it by the outer coating, traces a design with the knob on a plate of shellac or vulcanite. He then places the jar on an insulating stand, to enable him to transfer his hold to the knob, and traces another pattern on the cake with the outer coating. A mixture of flowers of sulphur and red-lead, which has previously been well dried and shaken together, is then sprinkled over the cake. The sulphur, having become negatively electrified by friction with the red-lead, adheres to the pattern which was traced with positive electricity, while the red-lead adheres to the other. The yellow and red colours render the patterns very conspicuous. The particles of sulphur (represented by the inner pattern in Fig. 393) arrange themselves in branching lines, while the red-lead (shown in the outer pattern) forms circular spots; whence it would appear that positive electricity travels along the surface more easily than negative. A similar difference has already been pointed out between positive and negative brushes.

CHAPTER XLI.

EFFECTS PRODUCED BY THE DISCHARGE OF CONDENSERS.

463. Discharge of Batteries.—The effects produced by the discharge of a Leyden jar or battery differ only in degree from those of an ordinary electric spark. The shock, which is smart even with a small jar, becomes formidable with a large jar, and still more with a battery of jars.

If a shock is given to a number of persons at once, they must form a chain by holding hands. The person at one end of the chain must place his hand on the outer coating of a charged jar, and the person at the other end must touch the knob. The shock will be felt by all at once, but somewhat less severely by those in the centre.

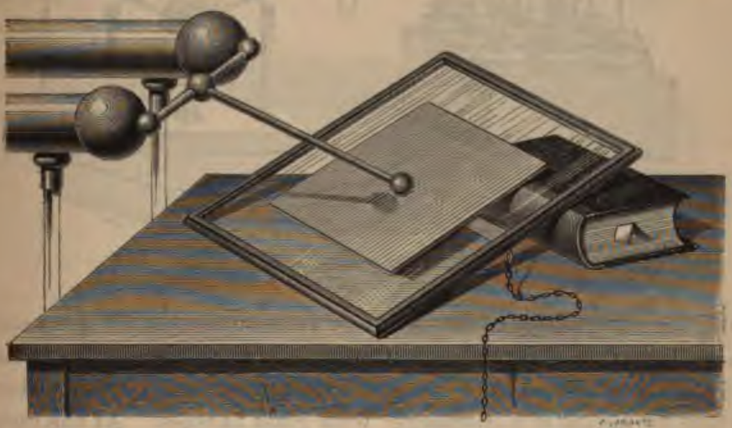

Fig. 394.—Coated Pane.

The *coated pane*, represented in Fig. 394, is simply a condenser, consisting of a pane of glass, coated on both sides, in its central portion, with tin-foil. Its lower coating is connected with the earth by a chain, and a charge is given to its upper coating by the machine. When it is charged, if a person endeavours to take up a coin laid upon its upper face, he will experience a shock as soon as his hand comes near it, which will produce involuntary contraction of his arm, and prevent him from taking hold of the coin.

464. Heating of Metallic Threads.—The discharge of electricity through a conducting system produces elevation of temperature, the amount of heat generated being the equivalent of the potential energy which runs down in the discharge, and which is jointly proportional to quantity of electricity and difference of potential. The incandescence of a fine metallic thread can be easily produced by the discharge of a battery. The thread should be made to connect the knobs *a b* of an apparatus called a *universal discharger;* these knobs being the extremities of two metallic arms supported on glass stems. One of the arms is connected with the external surface of the battery, and the other arm is then brought into connection with the internal surface by means of a discharger with glass handles. At the instant of the spark passing, the thread becomes red-hot, melts, burns, or volatilizes, leaving, in the latter cases, a coloured streak on a sheet of paper *c* placed behind it. When the thread is of gold, this streak is purple, and exactly resembles the marks left on walls when bell-ropes containing gilt thread are struck by lightning.

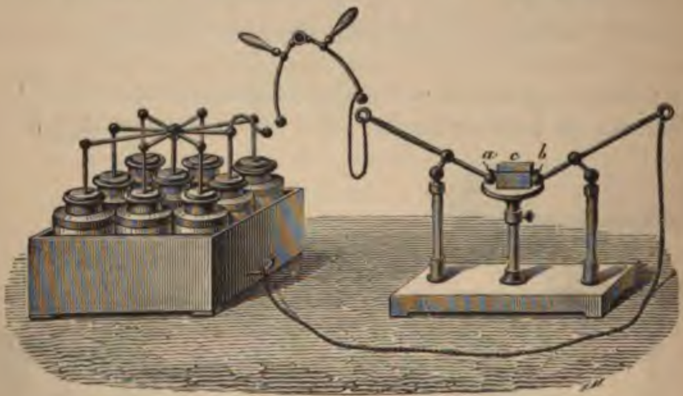

Fig. 395.—Universal Discharger.

465. Electric Portrait.—The volatilization of gold is employed in producing what are called electric portraits. The outline of a portrait of Franklin is executed in a thin card by cutting away narrow strips. Two sheets of tin-foil are gummed to opposite edges of the card, which is then laid between a gold-leaf and another card. The whole is then placed in a press (Fig. 396), the tin-foil being allowed to protrude, and strong pressure is applied. The press is placed on the table of the universal discharger, and the two knobs of the latter are connected with the two sheets of tin-foil. The discharge is then passed, the gold is volatilized, and the vapour, passing through the slits to the white card at the back, leaves purple traces which reproduce the design.

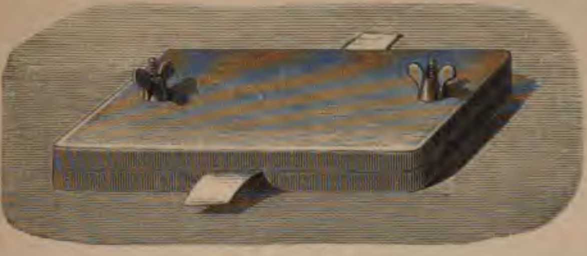
Fig. 396.—Press for Portrait.

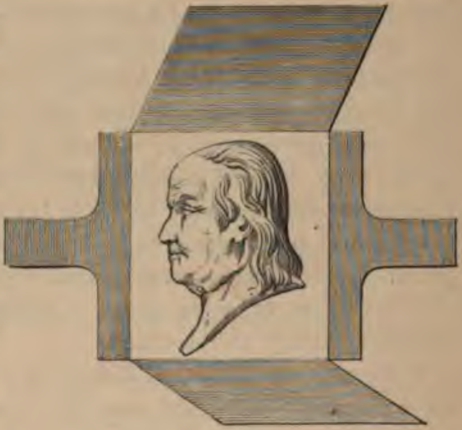
Fig. 397.—Arrangement for Portrait.

466. Velocity of Electricity.—Soon after the invention of the Leyden jar, various attempts were made to determine the velocity with which the discharge travels through a conductor connecting the two coatings. Watson, about 1748, took two iron wires, each more than a mile long, which he arranged on insulating supports in such a way that all four ends were near together. He held one end of each wire in his hands, while the other ends were connected with the two coatings of a charged jar. Although the electricity had more than a mile to travel along each wire before it could reach his hands, he could never detect any interval of time between the passage of the spark from the knob of the jar and the shock which he felt. The velocity was in fact far too great to be thus measured.

Wheatstone, about 1836, investigated the subject with the aid of the revolving mirror of which we have spoken above (§ 437). He connected the two coatings of a Leyden jar by means of a conductor which had breaks in three places, thus giving rise to three sparks. When the sparks were taken in front of the revolving mirror, the positions of the images indicated a retardation of the middle spark, as compared with the other two, which were taken near the two coatings of the jar, and were strictly simultaneous. The middle break was separated from each of the other two by a quarter of a mile of copper wire. He calculated that the retardation of the middle spark was $\frac{1}{1,152,000}$ of a second, which was therefore the time occupied in travelling through a quarter of mile of copper wire. This is at the rate of 288,000 miles per second, a greater velocity than that of light, which is only about 184,000 miles per second.

Since the introduction of electric telegraphs, several observations have been taken on the time required for the transmission of a signal. For instance, trials in Queenstown harbour, in July, 1856, when the two portions of the first Atlantic cable, on board the *Agamemnon* and *Niagara*, were for the first time joined into one conductor, 2500 miles long, gave about $1\frac{3}{4}$ seconds as the time of transmission of a signal from induction coils, corresponding to a velocity of only 1400 miles per second. In 1858, before again proceeding to sea, a quicker and more sensitive receiving instrument—Thomson's mirror galvanometer—gave a sensible indication of rising current at one end of 3000 miles of cable about a second after the application of a Daniell's battery at the other.

It seems to be fully established by experiment that electricity has no definite velocity, and that its apparent velocity depends upon various circumstances, being greater through a short than through a long line, greater (in a long line) with the greater intensity and suddenness of the source, greater with a copper than with an iron wire, and much greater in a wire suspended in air on poles than in one surrounded by gutta-percha and iron sheathing, and buried under ground or under water. In a long submarine line, a short sharp signal sent in at one end, comes out at the other as a signal gradually increasing from nothing to a maximum, and then gradually dying away.

467. Unit-jar.—For quantitative experiments on the effects of discharge, Lane's *unit-jar* has frequently been employed. One of its forms is represented in Fig. 398. It consists of a very small Leyden phial, having two knobs *a*, *b*, one connected with each coating, the distance between them being adjustable by means of a sliding rod. To measure the charge given to a jar or battery, the latter is placed upon an insulating support, its inner coating is connected with the conductor of the machine, and its outer coating is connected with the inner coating of the unit-jar. The outer coating of the unit-jar must be in connection with the ground. When the machine is worked, sparks pass between *a* and *b*, each spark being produced by the escape of a definite quantity of electricity from the outer coating of the battery, and indicating the addition of a definite amount to the charge of the inner coating. The charge is measured by counting the sparks.

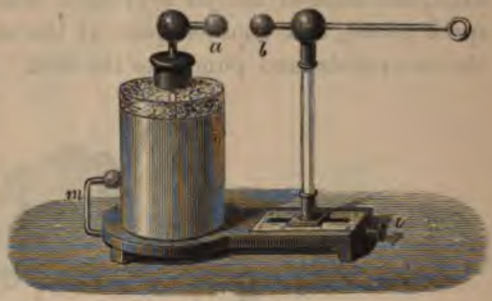

Fig. 398.—Unit-jar.

Snow Harris modified the arrangement by insulating the unit-jar instead of the battery. One coating of his unit-jar is connected with the battery, and the other with the conductor of the machine. The battery thus receives its charge through the unit-jar[1] by a succession of discharges between the knobs *a*, *b*, each representing a definite quantity of electricity.

Both arrangements, as far as their measuring power is concerned, depend upon the assumption that discharge between two given conductors, in a given relative position, involves the transfer of a definite quantity of electricity. This assumption implies a constant condition of the atmosphere. It may be nearly fulfilled during a short interval of time in one day, but is not true from one day to another. Moreover, it is to be remembered that, as dissipation is continually going on, the actual charge in the battery at any time is less than the measured charge which it has received.

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[1] Lane's arrangement might have been described by saying that the *outer coating* of the battery receives its negative charge from the earth through the unit-jar.

468. Mechanical Effects.—The effects of discharge through bad conductors are illustrated by several well-known experiments.

1. *Puncture of card.* A card is placed (Fig. 399) between two points connected with two conductors which are insulated from one another by means of a glass stem. The lower conductor having been connected with the outer coating of a Leyden jar which is held in the hand, the knob of the jar is brought near the upper conductor. A spark passes, and another spark at the same instant passes between the two points, and punctures the card. In performing this experiment it is observed that, if the points are not opposite each other, the perforation is close to the negative point. This want of symmetry appears to be due to the properties of the air. When arrangements are made for exhausting the air, it is found that, as the density of the air is diminished, the perforation takes place nearer to the centre.

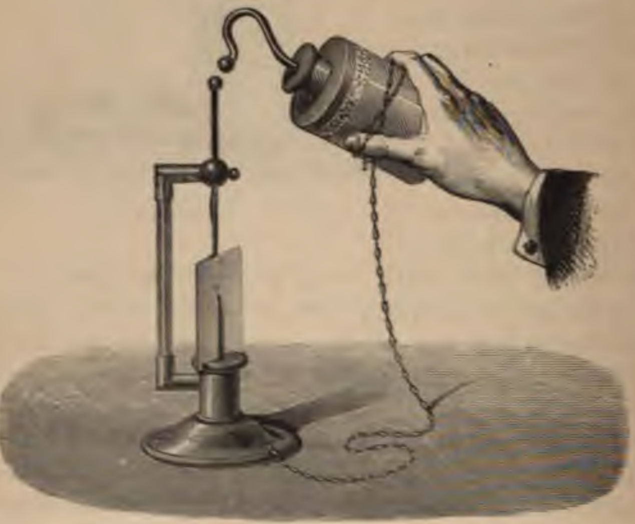

Fig. 399.—Puncture of Card.

The piercing of a card can very easily be effected by Holtz's machine. Its two conductors are connected with the two coatings of a small Leyden jar. The discharges between the poles will then consist of powerful detonating sparks in rapid succession; and if a sheet of paper or card be interposed, every spark will puncture a minute hole in it.

2. *Perforation of glass.* To effect the perforation of glass, a pane

of glass is supported on one end of a glass cylinder in whose axis there is a metallic rod terminating in a point which just touches the pane. Another pointed rod exactly over this, and insulated from it, is lowered until it touches the upper face of the pane. A powerful spark from a Leyden jar or battery is passed between the two points, and, if the experiment succeeds, a hole is produced by pulverization of the glass.

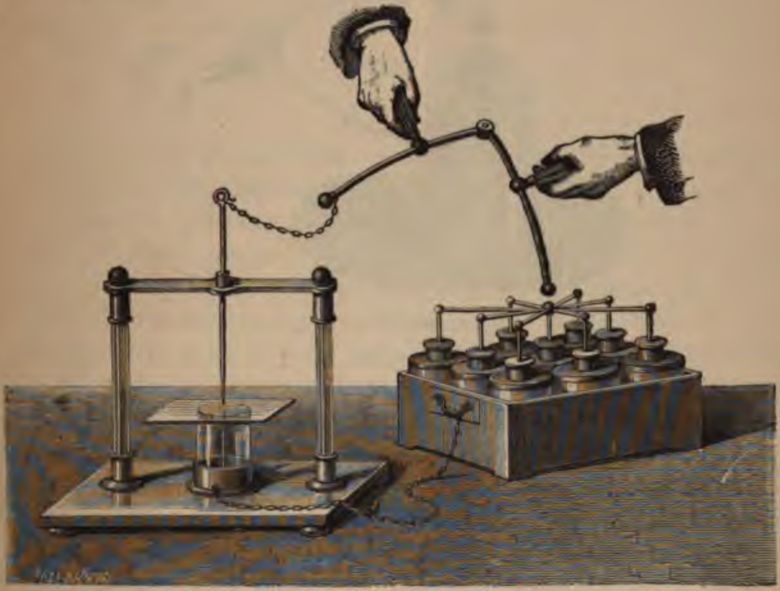

Fig. 400.—Puncture of Glass.

The experiment sometimes fails, by discharge taking place round the edge of the glass instead of through its substance. To prevent this, a drop of oil is placed on the upper face of the pane at the point where the hole is to be made; but this precaution does not always insure success, and, when the experiment has once failed, it is useless to try it again with the same piece of glass, for the electricity is sure to follow in the course which the first discharge has marked out for it.

469. Explosion of Mines.—If a strongly charged Leyden jar be discharged by means of a jointed discharger which has one of its knobs covered with gun-cotton, when the spark passes between the jar and this knob, the gun-cotton will be inflamed. Ordinary cotton mixed with powdered resin can be kindled in the same way.

A similar arrangement is often used for exploding mines. A fuse is employed containing two wires embedded in gutta-percha, but with their ends unprotected and near together. One of these wires is connected with the outer coating of a condenser, and the other is brought into communication with the inner coating. The discharge is thus made to pass between the ends within the fuse, and to ignite a very inflammable compound by which they are surrounded. Sometimes one of the wires, instead of being connected with the outer coating, is connected with the earth by means of a buried wire.

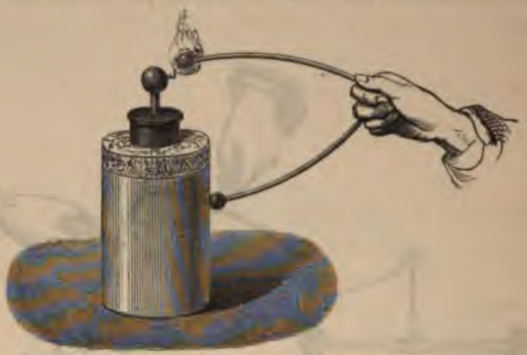

Fig. 401.—Gun-cotton Fired.

CHAPTER XLI^{A}.

ELECTROMETERS.

469 A. Object of Electrometers.—Electrometers are instruments for the measurement of differences of electrical potential. The gold-leaf electroscope, the straw-electroscope, and other instruments of the same type, afford rough indications of the difference of potential between the diverging bodies and the air of the apartment, and more measurable indications are given by the electrometers of Peltier and Dellmann; but none of these instruments are at all comparable in precision to the various electrometers which have been invented from time to time by Sir Wm. Thomson.

469 B. Attracted-disc Electrometers, or Trap-door Electrometers.—We shall first describe what Sir Wm. Thomson calls "Attracted-disc Electrometers." These instruments, one of which is represented in Figs. 401 A, 401 B, contain two parallel discs of brass g, h, with an aperture in the centre of one of them, nearly filled up by a light trap-door of aluminium f, which is supported in such a way as to admit of its electrical attraction towards the other disc being resisted by a mechanical force which can be varied at pleasure. The trap-door and the perforated plate surrounding it must have their faces as nearly as possible in one plane when the observation is taken, and, as they are electrically connected, they may then be regarded as forming *one disc of which a small central area is movable.* There is always attraction between the two parallel discs, except when they are at the same potential.

Let their potentials be denoted by V and V′, the electrical densities on their faces by ρ and ρ', and their mutual distance by D. We have seen (§ 445 Q) that, in such circumstances, ρ and ρ' are constant (except near the edges of the discs), opposite in sign, and equal, and that the intensity of force in the space between them is everywhere the same, and equal at once to $\frac{V-V'}{D}$ and to $4\pi\rho$. This force is jointly due to attraction by one plate and repulsion by the other, each of these having the intensity $2\pi\rho$, or half the total intensity.

Let A denote the area of the trap-door. The quantity of electricity upon it will be ρA, and the force of attraction which this experiences will be $\rho A \times 2\pi\rho = 2\pi\rho^2 A$, which we shall denote by F. Then from the equations

$$F = 2\pi\rho^2 A \quad , \quad \frac{V-V'}{D} = 4\pi\rho, \qquad (1)$$

we find, by eliminating ρ,

$$F = \frac{A}{8\pi}\left(\frac{V-V'}{D}\right)^2, \text{ or } V-V' = \pm D\sqrt{\frac{8\pi F}{A}}. \qquad (2)$$

469c. Absolute Electrometer.—In the *absolute electrometer*, which somewhat resembles Fig. 401 B turned upside down, the force of electrical attraction on the trap-door is measured by direct comparison with the gravitating force of known weights. This is done by first observing what weights must be placed on the trap-door to bring it into position when no electrical force acts (the plates being electrically connected), and by then removing the weights, allowing electrical force to act, and adjusting the plates at such a distance from one another, by the aid of a micrometer screw, that the trap-door shall again be brought into position. Then, in equation (2), F, A, and D are known, and the difference of potentials $V-V'$ can be determined. In the absolute electrometer, the perforated disc *h* is uppermost, so that the direction of electrical attraction on the trap-door is similar to the direction of the gravitating force of the weights. The reverse arrangement is usually adopted in the portable electrometer, which we shall next describe. In both instruments, the trap-door constitutes one end of a very light lever *fil* of aluminium, balanced on a horizontal axis.

469d. Portable Electrometer.—In the *portable electrometer* (Figs. 401 A, 401 B) this axis passes very accurately through the centre of gravity of the lever, the suspension being effected by means of a fine platinum wire *w w* tightly stretched, which is secured at its centre to the lever in such a manner that, when the trap-door comes into position, the wire is under torsion tending to draw back the disc from the attracting plate *g*. This torsion (except in so far as it is affected by causes of error such as temperature and gradual loss of elasticity) is always the same when the disc is in position, and as it is to be balanced in every observation by electrical attraction, the latter must also be always the same; that is to say, the quantity F in equations (2) is constant for all observations with the same instrument; whence it is obvious that V—V′ is directly proportional to D, the distance between the plates. The observation for difference of potential therefore consists in altering this distance until the trap-door comes into position. This is done by turning the micrometer screw, by means of the milled head *m*. The divided circle of the micrometer indicates the amount of turning for small distances, and whole revolutions are read off on the vertical scale traversed by the index carried by the arm *d*. The correct position is very accurately identified by means of two sights, one of them being attached to a fixed portion of the instrument, and the other to one end *l* of the lever. One of these sights moves up and down close in front of the other, and they are viewed through a lens *o* in front of both. This arrangement is also adopted in the absolute electrometer.

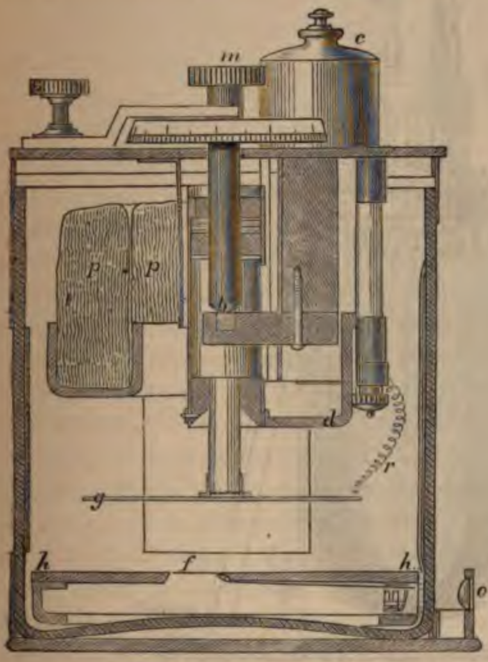

Fig. 401 A.—Portable Electrometer.

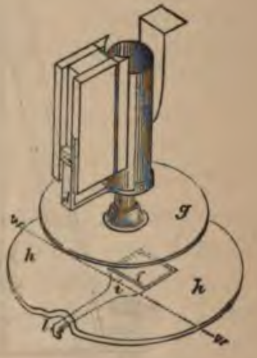

Fig. 401 B.—Parallel Discs.

One of the two parallel plates *h* is connected with the inner coating of a Leyden jar,[1] which, being kept dry within by means of pumice *p* wetted with sulphuric acid, retains a sufficient charge for some weeks. The other plate *g* is in communication, by means of the spiral wire *r*, with the insulated umbrella *c*, which can be connected with any external conductor; and, in order to determine the potential of any conductor which we wish to examine, two observations are taken, one of them giving the difference of potential between this conductor and the Leyden jar, and the other the difference between the earth and the jar. We thus obtain, by subtrac-

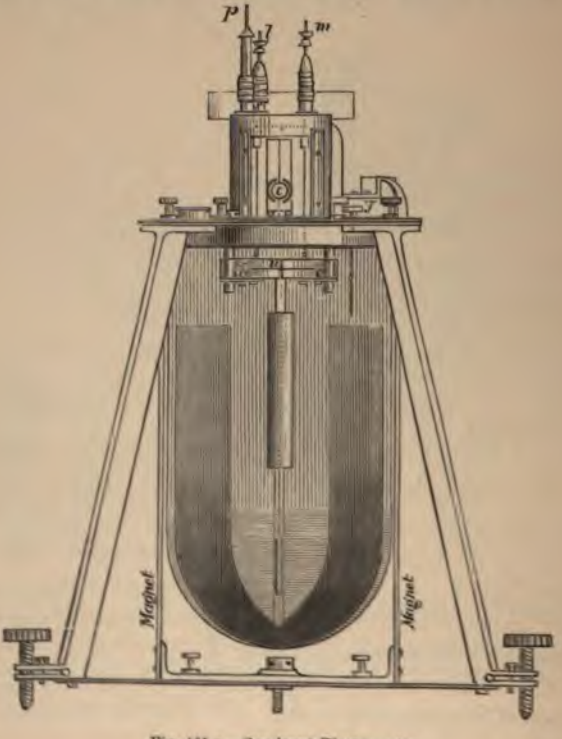

Fig. 401 c.—Quadrant Electrometer.

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[1] The use of the Leyden jar is to give constancy of potential. Its capacity is so much greater than that of the disc with which it is connected that the electricity which enters or leaves the latter in consequence of the inductive action of the other disc is no sensible fraction of its whole charge, and produces no sensible change in its potential. Its great capacity in comparison with the extent of surface exposed likewise tends to prevent rapid loss of potential by dissipation of charge.

tion, the difference of potential between the conductor in question and the earth.

469 E. Quadrant Electrometer.—The most sensitive instrument yet invented for the measurement of electrical potential is the *quadrant electrometer*, which is represented in front view in Fig. 401 C, some of its principal parts being shown on a larger scale in Figs. 401 D, 401 E.

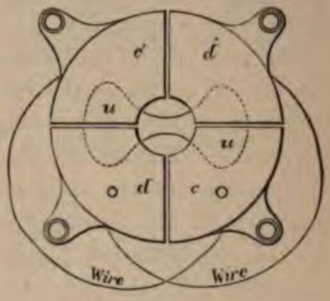

Fig. 401 D.—Needle and Quadrants.

In this instrument, the part whose movements give the indications is a thin flat piece of aluminium u, narrow in the middle and broader towards the ends, but with all corners rounded off. This piece, which is called the *needle*, and is represented by the dotted line in Fig. 401 D, is inclosed almost completely in what may be described as a shallow cylindrical box of brass, cut into four quadrants, c, d, c' d'. These parts are shown in plan in Fig. 401 D, and in front view in Fig. 401 C. The needle u is attached to a stiff platinum wire, which is supported by a silk fibre hanging vertically. The same wire carries a small concave mirror t (Fig. 401 C) for reflecting the light from an illuminated vertical slit. An image of the slit is thus formed at the distance of about a yard, and is received upon a paper scale of equal parts, by reference to which the movements of the image can be measured. The movements of the image depend upon the movements of the mirror, which are precisely the same as those of the needle. We have now to explain how the movements of the needle are produced.

One pair of opposite quadrants c c' are connected with each other, and with a stiff wire l projecting above the case of the instrument. The other quadrants d d' are in like manner connected with the other projecting wire m. The projecting parts l m are called the *chief electrodes*, and are to be connected respectively with the two conductors whose difference of potential is required, one of which is usually the earth. Suppose the needle to have a positive charge of its own, then if the potential of c and c' be higher (algebraically) than that of d and d', one end of the needle will experience a force urging it from c to d, and the other end will experience a force urging it from c' to d'. These two forces constitute a couple tending to turn the needle about a vertical axis. If the potential of c and c' be lower than that of d and d', the couple will be in the opposite direction. To prevent the needle from deviating too far under the action of this couple, and to give it a definite position when there is no electrical couple acting upon it, a small light magnet is attached to the back of the mirror, and by means of controlling magnets outside the case the earth's magnetism is overpowered, so that, whatever position be chosen for the instrument, the needle can be made to assume the proper zero position. In some instruments recently constructed, the magnets are dispensed with, and a bifilar suspension is substituted for the single silk fibre. The permanent electrification of the needle is attained by connecting it, by means of a descending platinum wire, with a quantity of strong sulphuric acid, which occupies the lower part of the containing glass jar. The acid, being an excellent conductor, serves as the inner coating of a Leyden jar, the outside of the glass opposite to it being coated with tin-foil, and connected with the earth. The acid at the same time serves the purpose of keeping the interior of the apparatus very dry. The charge is given to the jar through the *charging electrode* p, which can be thrown into or out of connection at pleasure. As the sensibility of the instrument increases with the potential of the jar, a *gauge* and *replenisher* are provided for keeping this potential constant. The *gauge* is simply an "attracted-disc electrometer," in which the distance between the parallel discs is never altered, so that the aluminium square only comes into position when the potential of one of the discs, which is connected with the acid in the jar, differs by a certain definite amount from the potential of the other, which is connected with the earth. A glance at the gauge shows, at any moment, whether the potential of the jar has the normal strength. If it has fallen below this point, the *replenisher* is employed to increase the charge.

This apparatus, which is separately represented, dissected, in Fig. 401 E, and is for simplicity omitted in Fig. 401 C, consists of a vertical stem of ebonite s, which can be rapidly twirled with the finger by means of a milled head y, and which carries two metal wings or *carriers*, b, b, insulated from each other. In one part of their revolution, these come in contact with two light steel springs $f\,f$, which simply serve to connect them for the instant with each other. In another part of their revolution, they come in contact with two other springs $e\;e$, connected respectively with the acid of the jar and with the earth. The first of these contacts takes place just before the wings emerge from the shelter of the larger metallic sectors or *inductors a a*, of which one is connected with the acid, and the other with the earth. Suppose the acid to have a positive charge. Then, at the instant of contact, an inductive movement of electricity takes place, producing an accumulation of negative electricity in the carrier which is next the positive inductor, and an accumulation of positive in the other. The next contacts are effected when the carrier which has thus acquired a positive charge is well under cover of the positive inductor, to which accordingly it gives up its electricity, for, being in great part surrounded by this inductor, and being connected with it by the spring, the carrier may be regarded as forming a portion of the interior of a concave conductor, and the electricity accordingly passes from it to the external surface, that is to the inductor, and to the acid connected with it, which form the lining of the jar. The negative electricity on the other carrier is, in like manner, given off to the other inductor, and so to the earth.

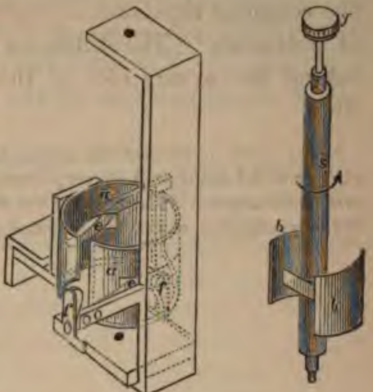

Fig. 401 E.—Replenisher.

The jar thus receives an addition to its charge once in every half-revolution of the replenisher; and, as these increments are very small, it is easy to regulate the charge so that the gauge shall indicate exactly the normal potential. If the charge is too strong, it can be diminished by turning the replenisher in the reverse direction.

469 F. Cage-electrometer.—In another form of electrometer, which has some advantages of its own, though now but little used, the observation for difference of potential consists in applying torsion to a glass fibre until the needle (a straight piece of aluminium wire) which it carries, is forced, against electrical repulsion, to assume a definite position marked by sights. The repulsion, which acts upon the two ends of the needle so as to produce a couple, is exerted by two vertical brass plates, which are connected with the needle by means of fine platinum wires dipping in sulphuric acid at the bottom of a Leyden jar. The needle and the plates which repel it are thus at the potential of the jar. The repulsion between them is modified by the influence of a cage of brass wire, which surrounds them, and which is connected with the conductor whose potential is to be examined. If this conductor has the same potential as the jar, there is no repulsion. If its potential differs either way from that of the jar, the couple of repulsion is proportional to the square of this difference of potentials.[1] The difference of potential is therefore obtained by taking the square root of the number of degrees of torsion of the fibre.

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[1] In a given position of the needle, the quantities of electricity upon it and upon the plates which repel it are both proportional to this difference of potentials, and the distribution is invariable. Hence (§ 420) the force of repulsion is proportional to the product of the two quantities, that is to the square of either of them.

CHAPTER XLII.

ATMOSPHERIC ELECTRICITY.

470. Resemblance of Lightning to the Electric Spark.—The resemblance of the effects of lightning to those of the electric spark struck the minds of many of the early electricians. Lightning, in fact, ruptures and scatters non-conducting substances, inflaming those which are combustible; heats, reddens, melts, and volatilizes metals; and gives shocks, more or less severe, and frequently fatal, to men and animals; all of these being precisely the effects of the electric spark with merely a difference of intensity. We may add that lightning leaves behind it a characteristic odour precisely similar to that which is observed near an electrical machine when it is working, and which we now know to be due to the presence of ozone. Moreover, the form of the spark, its brilliancy, and the detonation which attends it, all remind one forcibly of lightning.

To Franklin, however, belongs the credit of putting the identity of the two phenomena beyond all question, and proving experimentally that the clouds in a thunder-storm are charged with electricity. This he did by sending up a kite, armed with an iron point with which the hempen string of the kite was connected. To the lower end of the string a key was fastened, and to this again was attached a silk ribbon intended to insulate the kite and string from the hand of the person holding it. Having sent up the kite on the approach of a storm, he waited in vain for some time even after a heavy cloud had passed directly over the kite. At length the fibres of the string began to bristle, and he was able to draw a strong spark by presenting his knuckle to the key. A shower now fell, and, by wetting the string, improved its conducting power, the silk ribbon being still kept dry by standing under a shed. Sparks in rapid succession were drawn from the key, a Leyden jar was charged by it, and a shock given.

45749A

Shortly before this occurrence, Dalibard, acting upon a published suggestion of Franklin, had erected a pointed iron rod on the top of a house near Paris. The rod was insulated from the earth, and could be connected with various electrical apparatus. A thunder-storm having occurred, a great number of sparks, some of them of great power, were drawn from the lower end of the rod.

These experiments were repeated in various places, and Richmann of St. Petersburg, while conducting an investigation with an apparatus somewhat resembling that of Dalibard, received a spark which killed him on the spot.

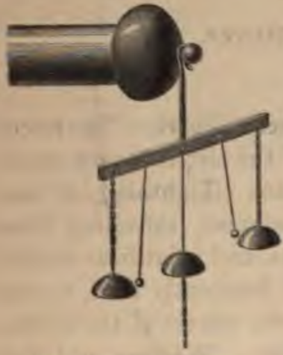


Fig. 402.—Electric Chimes.

472. Electric Chimes.—Franklin devised an apparatus for giving warning when the insulated rod is charged with electricity. It consists (Fig. 402) of a metal bar, carrying three bells with two clappers between them. The two extreme bells are hung from the bar by metallic chains. The middle one is hung by a silk thread, and connected with the ground. The clappers are also hung by silk threads. When the bar is electrified, the clappers are first attracted by the two extreme bells, and then repelled to the middle bell, through which they discharge themselves, to be again attracted and repelled, thus keeping up a continual ringing as long as the bar remains electrified.

473. Duration of Lightning.—It appears that thunder-clouds must be regarded as charged masses of considerable conducting power. The discharges which produce lightning and thunder occur sometimes between two clouds, and sometimes between a cloud and the earth. The duration of the illumination produced by lightning is certainly less than the ten-thousandth of a second. This has been established by observing a rapidly rotating disc (Fig. 403) divided into sectors alternately black and white. If viewed by daylight, the disc appears of a uniform gray; and if lightning, occurring in the dark, renders the separate sectors visible, the duration of its light must be less than the time of revolving through the breadth of one sector. The experiment has been tried with a disc divided into 60 sectors, and making 180 revolutions per second, so that the time of turning through the

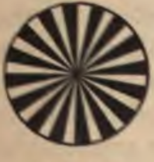


Fig. 403.—Duration of Flash.

space occupied by one sector is $\frac{1}{60}$ of $\frac{1}{180}$ of a second, that is, $\frac{1}{10800}$. When the disc, turning with this velocity, is rendered visible by lightning, the observer sees black and white sectors with gray ones between them. For the black and white sectors to be seen sharply defined, without intermediate gray, it would be necessary that the illumination should be absolutely instantaneous.

476. Thunder.—Thunder frequently consists of a number of reports heard in succession. This can be explained by supposing that (as in the experiment of the spangled tube, § 440) discharge occurs at several places at once. The reports of these explosions will be heard in the order of their distance from the observer. If, for example, the lines of discharge form the zig-zag M N (Fig. 404), an observer at O will hear first the explosion at *a*, then, a little later, the five explosions at *m*, *n*, *r*, *s*, *t*; he will consequently observe an increase in the intensity of the sound.

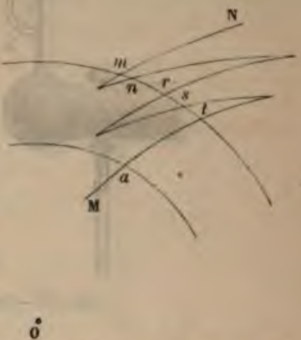


Fig. 404.—Simultaneous Explosions.

477. Shock by Influence.—Persons near whom a flash of lightning passes, frequently experience a severe shock by induction. This is analogous to the phenomenon, first observed by Galvani, that a skinned frog in the neighbourhood of an electrical machine, although dead, exhibits convulsive movements every time a spark is drawn from the conductor. In like manner, if Volta's pistol (§ 443) be placed on the wooden supports of an electrical machine, and its knob be connected with the ground by a chain, on drawing a spark from the machine, another spark will pass in the interior of the pistol, and fire it off.

478. Lightning-conductors.—Experience having shown that electricity travels in preference through the best conductors, it is easy to understand that, if a building be fitted with metallic rods terminating in the earth, lightning will travel through these instead of striking the building. But further, if these rods terminate above in a point, they may exercise a preventive influence by enabling the earth and clouds to exchange their opposite electricities in a gradual way, just as the conductor of a machine is prevented from giving powerful sparks by presenting to it a sharp point connected with the earth.

While the electrical machine is working powerfully, and the quadrant electroscope shows a strong charge, let a pointed metallic rod be presented, as in Fig. 405; the pith-ball will immediately fall back to the vertical position, and it will be found impossible to draw a spark from any part of the conductor. If the experiment is performed in the dark, the point will be seen to be tipped with light; and a similar appearance is sometimes observed on the tops of lightning-rods and of ships' masts. In the latter position it is known to sailors as *St. Elmo's fire*.

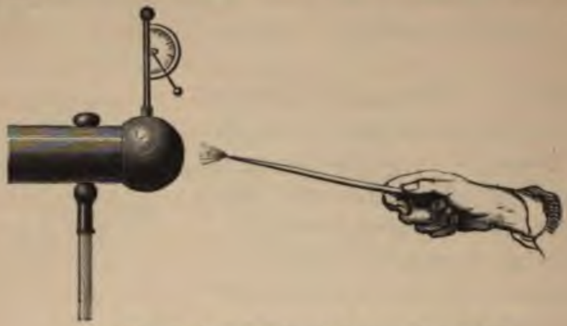


Fig. 405.—Conductor Discharged by presenting a Point.

479. Construction of Lightning-conductors.—A badly constructed lightning-conductor may be a source of danger, instead of a protection. The following conditions should always be complied with:—

1. The connection with the ground should be continuous.

2. The conductor must be everywhere of so large a section that it will not be melted by lightning passing through it. The French Academy of Sciences recommend that the section for iron rods should be nowhere less than 2·25 centimetres, or $\frac{9}{10}$ of an inch.

3. The earth contact must be good. The conductor may be connected at its base with the iron pipes which supply the neighbourhood with water or gas; or it may terminate in the water of a well or pond. Failing these, it should be provided with branches traversing the soil in different directions, and surrounded by coke, which is a good conductor.

4. At no part of its course above ground should it come near to the metal pipes which supply the house with water or gas, nor to any large masses of metal in the house. All large masses of metal on the outside of the house, such as lead roofing, should be well connected with the conductor.

5. The extreme point should be sharp. A former commission of the Academy recommended a platinum point, which should be connected with the iron by welding. But as this construction is both difficult and expensive, later directions have been issued recommending a gilded copper cone, screwed on to the iron, as shown in Fig. 407, which is half the actual size. This form of termination is better than a needle point, because less liable to fusion.

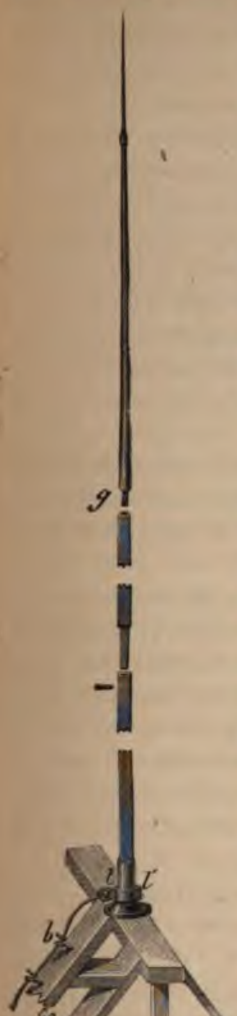


Fig. 406. — Lightning-conductor.

The general arrangement is represented in Fig. 406. The rod has a diameter of 2 or 3 inches at its base, and gradually tapers upwards to the place where the point is screwed on. The descending portion *b* is connected with the base of this rod by the broad band *ll'*.

480. Ordinary Electricity of the Atmosphere.—The presence of electricity in the upper regions of the air is not confined to thunder-clouds, but can be detected at all times. In fine weather this electricity is almost invariably positive, but in showery or stormy weather negative electricity is as frequently met with as positive; and it is in such weather that the indications of electricity, whether positive or negative, are usually the strongest.

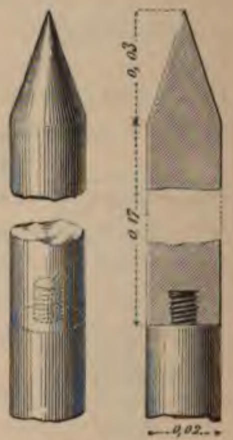


Fig. 407.—Gilded Copper Point.

480 A. Methods of obtaining Indications.—One of the early methods of observing atmospheric electricity consisted in shooting up an arrow, attached to a conducting thread, having at its lower end a ring, which was laid upon the top of a gold-leaf electroscope. As the arrow ascends higher, the leaves diverge more and more with electricity of the same sign as that overhead; and they remain divergent after the ring has been lifted off by the movement of the arrow.

Sometimes, instead of the arrow, a point on the top of the electroscope is employed to collect electricity from the air, as in Fig. 408. Both these methods are very uncertain in their action.

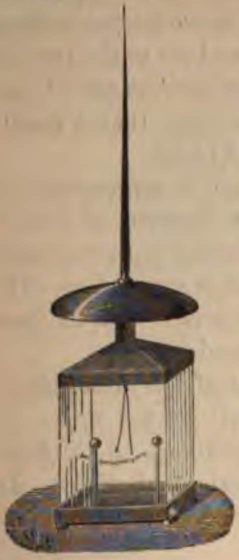
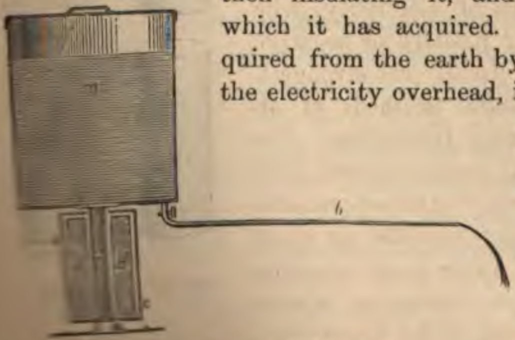


Fig. 408.—Early Form of Electrometer.

A better method of collecting electricity from the air was long ago devised by Volta, who employed for this purpose a burning match attached to the top of a rod connected with the gold-leaves or straws of his electroscope. If there is positive electricity overhead, its influence causes negative electricity to collect at the upper end of the rod, whence it passes off by convection in the products of combustion of the match, leaving the whole conducting system positively electrified. In like manner, if the electricity overhead be negative, the system will be left negatively electrified.

Another method which, in the hands of Peltier, Quetelet, and Dellmann, has yielded good results, consists in first exposing, in an elevated position such as the top of a house, a conducting ball supported on an insulating stand, and, while exposed, connecting it with the earth; then insulating it, and examining the charge which it has acquired. This charge, being acquired from the earth by the inductive action of the electricity overhead, is opposite in sign to the inducing electricity.



[illegible] A.—Water-dropping Collector.

Another method, which in principle resembles that of Volta, but is speedier in its action, has been introduced by Sir W. Thomson. It consists in allowing a fine stream of [illegible] from an insulated metallic vessel, through a pipe, [illegible] through an open window or other aperture in the wall of a house, so that the nozzle from which the water flows is in the open air. The apparatus for this purpose, called the water-dropping collector, is represented in Fig. 408 A. *a* is a copper can, containing water, which can be discharged through the brass pipe *b* by turning a tap. The mode of insulation is worthy of notice. The can is supported on a glass stem *c*, which is surrounded, without contact, by a ring or rings of pumice *dd*, moistened with sulphuric acid. These are protected by an outer case of brass *ee*, having a hole in its top rather larger than the glass stem, the brass being separated from the moist pumice by an inner case of gutta-percha. The acid needs renewal about once in two months.

In severe frost, burning matches can be used instead of water, and are found to give identical indications. Whether water or match be used, the principle of action[1] is that, as long as any difference of potential exists between the insulated conductor and the point of the air where the issuing stream (whether of water or smoke) ceases to be one continuous conductor, and begins to be a non-conductor or a succession of detached drops, so long will each drop or portion that detaches itself carry off either positive or negative electricity, and thus diminish the difference of potential. This is an application of the principle of § 445 B, that electricity tends to travel from places of higher to places of lower potential. The time required to reduce the system to the potential which exists at the point above specified, is practically about half a minute with the water-jet, and from half a minute to a minute or more, according to the strength of the wind, with a match.

The water-dropper is the most convenient collecting apparatus when the observations are taken always in the same place. For portable service, Sir Wm. Thomson employs blotting-paper, steeped in solution of nitrate of lead, dried, and rolled into matches. The portable electrometer carries a light brass rod or wire projecting upwards, to the top of which the matches can be fixed.

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[1] The following quotation from an article by Sir W. Thomson puts the matter very clearly:—"If, now, we conceive an elevated conductor, first belonging to the earth, to become insulated, and to be made to throw off, and to continue throwing off, portions from an exposed part of its surface, this part of its surface will quickly be reduced to a state of no electrification, and the whole conductor will be brought to such a potential as will allow it to remain in electrical equilibrium in the air, with that portion of its surface neutral. In other words, the potential throughout the insulated conductor is brought to be the same as that of the particular equi-potential surface in the air, which passes through the point of it from which matter breaks away. A flame, or the heated gas passing from a burning match, does precisely this: the flame itself, or the highly heated gas close to the match, being a conductor which is constantly extending out, and gradually becoming a non-conductor. The drops [into which the jet from the water-dropper breaks] produce the same effects, with more pointed decision, and with more of dynamical energy to remove the rejected matter, with the electricity which it carries, from the neighbourhood of the fixed conductor."—*Nichol's Cyclopædia*, second edition, art. "Electricity, Atmospheric."

480 B. Interpretation of Indications.—We have seen that the collecting apparatus, whether armed with water-jet or burning match, is merely an arrangement for reducing an insulated conductor to the potential which exists at a particular point in the air. An electrometer will then show us the difference between this potential and that of any other given conductor, for example the earth. The earth offers so little resistance to the passage of electricity, that any temporary difference of potential which may exist between different parts of its surface, must be very slight in comparison with the differences of potential which exist between different points in the non-conducting atmosphere above it. As there is no possible method of determining absolute potential, since all electric phenomena would remain unchanged by an equal addition to the potentials of all points, it is convenient to assume, as the zero of potential, that of the most constant body to which we have access, namely the earth; and under the name earth we include trees, buildings, animals, and all other conductors in electrical communication with the soil.

Now we find that, as we proceed further from the earth's surface, whether upwards from a level part of it, or horizontally from a vertical part of it, such as an outer wall of a house, the potential of points in the air becomes more and more different from that of the earth, the difference being, in a broad sense, simply proportional to the distance. Hence we can infer[1] that there is electricity residing on the surface of the earth, the density of this electricity, at any moment, in the locality of observation, being measured by the difference of potential which we find to exist between the earth and a given point in the air near it. Observations of so-called atmospheric electricity[2] made in the manner we have described, are in fact simply determinations of the quantity of electricity residing on the earth's surface at the place of observation. The results of observations so made are however amply sufficient to show that electricity residing in the atmosphere is really the main cause of the variations observed. A charged cloud or body of air induces electricity of the opposite kind to its own on the parts of the earth's surface over which it passes; and the variations which we find to occur in the electrical density at the parts of the surface where we observe, are so rapid and considerable, that no other cause but this seems at all adequate to account for them. We may therefore safely assume that the difference of potential which we find, in increasing our distance from the earth, is mainly due to electricity induced on the surface of the earth by opposite electricity in the air overhead.

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[1] By § 445 I, if ρ denote the quantity of electricity per unit area on an even part of the earth's surface, the force in the neighbouring air is $4\pi\rho$. This must be equal to the change of potential in going unit distance (§ 445 D). If potential increases positively, ρ is negative.

[2] No good electrical observations have yet been made in balloons, and very little is known regarding the distribution of electricity at different heights in the air. A method of gauging this distribution by balloon observations is suggested by the principles of § 445 G, which show that, when the lines of force are vertical, and the tubes of force consequently cylindrical, the difference of electrical force at different heights is proportional to the quantity of electricity which lies between them.

As electrical density is greater on projecting parts of a surface than on those which are plane or concave, we shall obtain stronger indications on hills than in valleys, if our collecting apparatus be at the same distance from the ground in both cases. Under a tree, or in any position excluded from view of the sky, we shall obtain little or no effect.

480c. Results of Observation.—The only regular series of observations which have as yet been taken[1] with Sir Wm. Thomson's instruments, consist of two years' continuous observations with self-recording apparatus at Kew Observatory; and two years' observations, at three stated times daily, and at other irregular times, at Windsor in Nova Scotia (lat. 45° N.) The electrometer used at Kew was an earlier form of the quadrant electrometer already described; and the autographic registration was effected by throwing the image of a bright point (a small hole with a lamp behind it) upon a sheet of photographic paper drawn upwards by clock-work, whereas the movements of the image, formed by means of the mirror attached to the needle, were horizontal. The curves thus obtained give very accurate information respecting the potential of the air at the point of observation, when of moderate strength; but fail to record it when of excessive strength, as the image on these occasions passed out of range. The Windsor observations were taken with the cage-electrometer, of which two forms were employed, one being much more sensitive than the other. The more sensitive form was usually employed. When the potential became inconveniently strong, the first step was to shorten the discharging pipe by screwing off some of its joints. This reduced the strength of potential in about the ratio of 3 : 1; but even this reduction was often not enough for the more sensitive instrument, and on such occasions the other (which was intended as a portable electrometer) was employed instead. As the ratio of the indications of the two instruments was known, a complete comparison of potentials in all weathers was thus obtained. The results are as follows.

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[1] The observations at Windsor, N.S., and at Kew, are described in three papers by the editor of this work, *Proc. R. S.*, June 1863, January 1865, and *Trans. R. S.*, December 1867. Dellmann's observations at Kreuznach, which were taken with apparatus devised by himself, are described in *Phil. Mag.* June 1858. Quetelet's observations (taken with Peltier's apparatus) are described in his volume *Sur le Climat de la Belgique* (Brussels, 1849).

Employing a unit in terms of which the average fine-weather potential for the year was +4, the potential was seldom so weak as 1, though on rare occasions it was for a few minutes as low as 0·1. In wet weather, especially with sudden heavy showers, the potential was often as strong as ±20 to ±30, and it was fully as strong during hail. With snow, the average strength was about the same as with heavy rain, but it was less variable, and the sign was almost always positive. Occasionally, with high wind accompanying snow, during very severe frost, it was from +80 to +100, or even higher. With fog, it was always positive, averaging about +10. In thunder-storms it frequently exceeded ±100, and on a few occasions exceeded −200. There was usually a great predominance of negative potential in thunder-storms. Change of sign was a frequent accompaniment of a flash of lightning or a sudden downpour of rain. At all times, there was a remarkable absence of steadiness as compared with most meteorological phenomena, wind-pressure being the only element whose fluctuations are at all comparable, in magnitude and suddenness, with those of electrical potential. Even in fine weather, its variations during two or three minutes usually amount to as much as 20 per cent. In changeable and stormy weather they are much greater; and on some rare occasions it changes so much from second to second that, notwithstanding the mitigating effect of the collecting process, which eases off all sudden changes, the needle of the electrometer is kept in a continual state of agitation.

480 D. Annual and Diurnal Variations.—Observations everywhere[1] concur in showing that the average strength of potential is greater in winter than in summer; but the months of maxima and minima appear to differ considerably at different places. The chief maximum occurs in one of the winter months, varying at different places from the beginning to the end of winter; and the chief minimum occurs everywhere in May or June. Both Kew and Windsor show distinctly two maxima in the year, but Brussels, and apparently Kreuznach, show only one. The ratio of the highest monthly average to the lowest is at Kew about 2·5, at Windsor 1·9, and at Kreuznach 2·0.

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[1] The remarks in this section express the results of observation at places all of which are in the north temperate zone.

The Kew observations, being continuous, are specially adapted to throw light on the subject of diurnal variation. They distinctly indicate for each month two maxima, which in July occur at about 8 A.M. and 10 P.M., in January about 10 A.M. and 7 P.M., and in spring and autumn about 9 and 9. The result of the Brussels observations is about the same.

481. Causes of Atmospheric Electricity.—Various conjectures have been hazarded regarding the sources of atmospheric electricity; but little or no certain knowledge has yet been obtained on this subject. Evaporation has been put forward as a cause, but, as far as laboratory experiments show, whenever electricity has been generated in connection with evaporation, the real source has been friction, as in Armstrong's hydro-electric machine. The chemical processes involved in vegetation have also been adduced as causes, but without any sufficient evidence. It is perhaps not too much to say that the only natural agent which we know to be capable of electrifying the air is the friction of solid and liquid particles against the earth and against each other by wind. The excessively strong indications of electricity observed during snow accompanied by high wind, favour the idea that this may be an important source.

Without knowing the origin of atmospheric electricity, we may, however, give some explanation of the electrical phenomena which occur both in showers and in thunder-storms. Very dry air is an excellent non-conductor; very moist air has, on the other hand, considerable conducting power. When condensation takes place at several centres, a number of masses of non-conducting matter are transformed into conductors, and the electricity which was diffused through their substance passes to their surfaces. These separate conductors influence one another. If one of them is torn asunder while under influence, its two portions may be oppositely charged; and if rain falls from the under surface of a cloud which is under the influence of electricity above it, the rain which falls may have an opposite charge to the portion which is left suspended.

The coalescence of small drops to form large ones, though it increases the electrical density on the surfaces of the drops, does not increase the total quantity of electricity, and therefore (§ 445 K) cannot directly influence the observed potential.

Thunder-storms and other powerful manifestations of atmospheric electricity seem to be accompaniments of very sudden and complete condensation which gives unusually free scope to the causes of irregular distribution just indicated.

483. Hail.—Hail has sometimes been ascribed to an electrical origin, and a singular theory was devised by Volta to account for the supposed fact that hailstones are sustained in the air. He imagined that two layers of cloud, one above the other, charged with opposite electricities, kept the hailstones continually moving up and down by alternate attraction and repulsion. An experiment called *electric hail* is sometimes employed to illustrate this idea. Two metallic plates are employed (Fig. 409), the lower one connected with the earth, and the upper one with the conductor of the electrical machine, and pith-balls are placed between them. As the machine is turned, the balls fly rapidly backwards and forwards from one plate to the other.

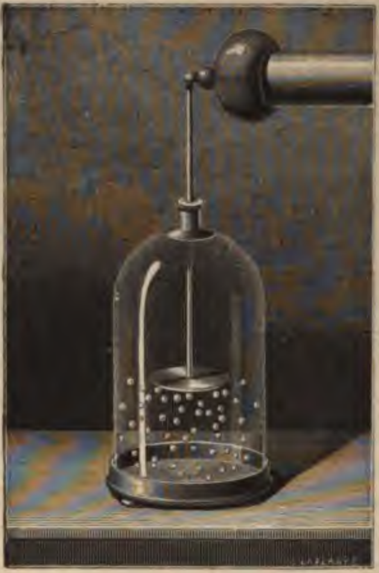

Fig. 409.—Electric Hail.

484. Waterspouts.—Waterspouts, being often accompanied by strong manifestations of electricity, have been ascribed by Peltier and others to an electrical origin; but the account of them given in the subjoined note appears more probable.[1]

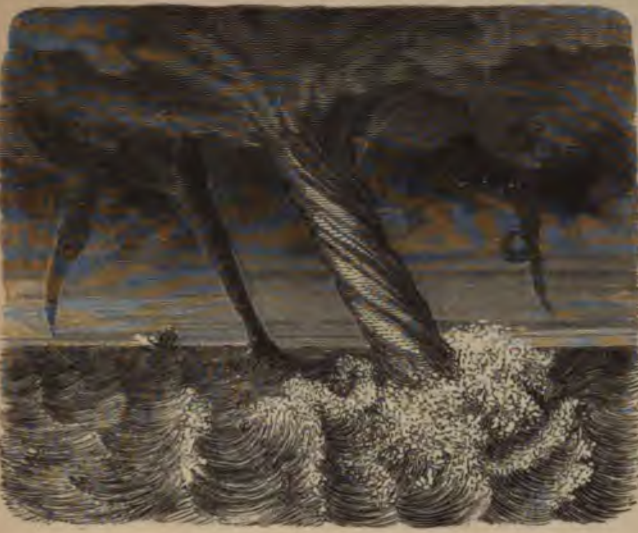

Fig. 410.—Waterspouts.

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[1] "On account of the centrifugal force arising from the rapid gyrations near the centre of a tornado, it must frequently be nearly a vacuum. Hence when a tornado passes over a building, the external pressure, in a great measure, is suddenly removed, when the atmosphere within, not being able to escape at once, exerts a pressure upon the interior, of perhaps nearly fifteen pounds to the square inch, which causes the parts to be thrown in every direction to a great distance. For the same reason, also, the corks fly from empty bottles, and everything with air confined within explodes. When a tornado happens at sea, it generally produces a waterspout. This is generally first formed above, in the form of a cloud shaped like a funnel or inverted cone. As there is less resistance to the motions in the upper strata than near the earth's surface, the rapid gyratory motion commences there first. . . . This draws down the strata of cold air above, which, coming in contact with the warm and moist atmosphere ascending in the middle of the tornado, condenses the vapour and forms the funnel-shaped cloud. As the gyratory motion becomes more violent, it gradually overcomes the resistances nearer the surface of the sea, and the vertex of the funnel-shaped cloud gradually descends lower, and the imperfect vacuum of the centre of the tornado reaches the sea, up which the water has a tendency to ascend to a certain height, and thence the rapidly ascending spiral motion of the atmosphere carries the spray upward, until it joins the cloud above, when the waterspout is complete. The upper part of a waterspout is frequently formed in tornadoes on land. When tornadoes happen on sandy plains, instead of waterspouts they produce the moving pillars of sand which are often seen on sandy deserts."—W. Ferrel, in *Mathematical Monthly*. See note § 406.

MAGNETISM.

CHAPTER XLIII.

GENERAL STATEMENT OF FACTS AND LAWS.

485. Magnets, Natural and Artificial.—Natural magnets, or *lodestones*, are exceedingly rare, although a closely allied ore of iron, capable of being strongly acted on by magnetic forces, and hence called *magnetic iron-ore,* is found in large quantity in Sweden and elsewhere. Artificial magnets are usually pieces of steel, which have been permanently endowed with magnetism by methods which we shall hereafter describe. Magnets are chiefly characterized by the property of attracting iron, and by the tendency to assume a particular orientation when freely suspended.

486. Force Greatest at the Ends.—The property of attracting iron is very unequally manifested at different points of the surface of a magnet. If, for example, an ordinary bar-magnet be plunged in iron-filings, these cling in large quantity to the terminal portions, and leave the middle bare, as in the lower diagram of Fig. 411. If the magnet is very thick in proportion to its length, we may have filings adhering to all parts of it, but the quantity diminishes rapidly towards the middle. The name *poles* is used, in a somewhat loose sense, to denote the two terminal portions of a magnet, or to denote two points, not very accurately defined, situated in these portions. The middle portion, to which the filings refuse to adhere, is called *neutral.*

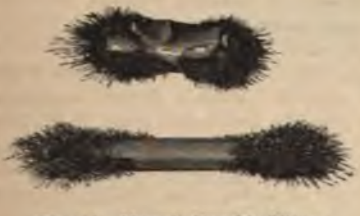

Fig. 411.—Magnets dipped in Filings.

487. Lines Formed by Filings.—If a sheet of card is laid horizontally upon a magnet, and wrought-iron filings are sifted over it, these will, with the assistance of a few taps given to the card, arrange themselves in a system of curved lines, as shown in Fig. 412. These lines give very important indications both of the direction and intensity of the force produced by the magnet at different points of the space around it.[1] They cluster very closely about the two poles *p p*, and thus indicate the places where the force is most intense.

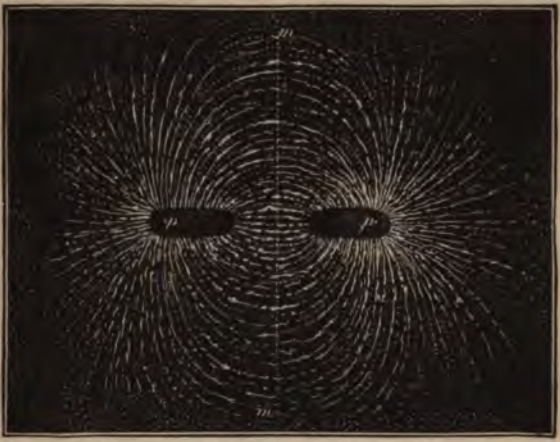

Fig. 412.—Magnetic Curves.

488. Curve of Intensities.—Some idea may be obtained of the relative intensities of magnetic force at different points in the length of a magnet, by measuring the weights of iron which can be supported at them. Much better determinations can be obtained either by the use of the torsion-balance, or by counting the number of vibrations made by a small magnetized needle when suspended opposite different parts of the bar, the bar being in a vertical position, and the vibrations of the needle being horizontal. The intensity of the force is nearly as the square of the number of vibrations; on the same principle that the force of gravity at different places is proportional to the square of the number of vibrations of a pendulum (§ 47). Both these methods of determination were employed by Coulomb, who was the first to make magnetism an accurate science; and the results which he obtained are represented by the curve of intensities A M B (Fig. 413). M is the middle of the bar, O one end of it, and the ordinates of the curve (that is, the distances of its points from the line O X) represent the intensities of force at the different points in its length. The curve was constructed from observations of the force at several points in the length; but in dealing with the observation made opposite the very end, the force actually observed was multiplied by 2. Perfect symmetry was found between the intensities over the two halves of the length. In the figure we have inverted the curve for one half, in order to indicate an opposition of properties, which we shall shortly have to describe. The curves of intensities for two magnets of different sizes but of the same form are usually similar.

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[1] The lines formed by the filings may be called the lines of *effective force for particles only free to move in the plane of the card*. The lines of total force cut the card at various angles, and are at some places perpendicular to it, as shown by the filings standing on end. For the definition of lines of magnetic force, see § 494 A.

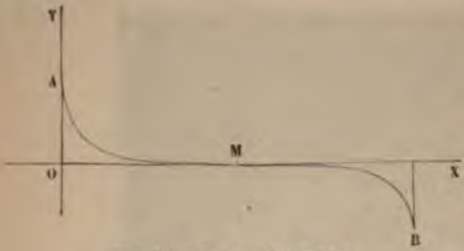

Fig. 413.—Curve of Intensities.

489. Magnetic Needle.—Any magnet freely suspended near its centre is usually called a *magnetic needle*, or more properly a *magnetized needle*. One of its most usual forms is that of a very elongated rhombus of thin steel, having, very near its centre, a concavity or *cup* by means of which it can be balanced on a point. When it is thus balanced horizontally, it does not, like a piece of ordinary matter, remain in equilibrium in all azimuths,[1] but assumes one particular direction, to which it always comes back after displacement. In this position of stable equilibrium, one of its ends points to magnetic north, and the other to magnetic south, which differ in general by several degrees from geographical (or true) north and south. This is the principle on which compasses are constructed.

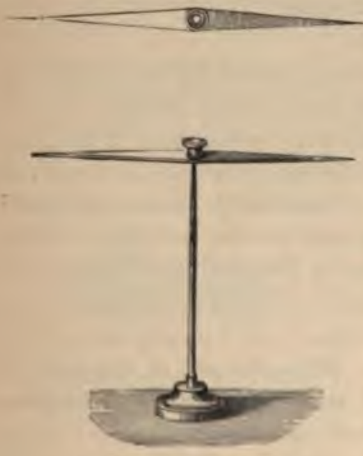

Fig. 414.—Magnetized Needle.

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[1] All lines in the same vertical plane are said to have the same *azimuth*. Azimuthal angles are angles between vertical planes, or between horizontal lines. The azimuth of a line when stated numerically, is the angle which the vertical plane containing it makes with a vertical plane of reference, and this latter is usually the plane of the meridian.

490. Declination.—The difference between magnetic and true north, or the angle between the magnetic meridian and the geographical meridian, is called *magnetic declination*.[1] It is very different at different places, and at a given place undergoes a gradual change from year to year, besides smaller changes, backwards and forwards, which are continually taking place. At Greenwich, at the present time, its value is about 20° W., that is, magnetic north is west of true north by this amount. For the British Isles generally its value is from 20° to 30° W.

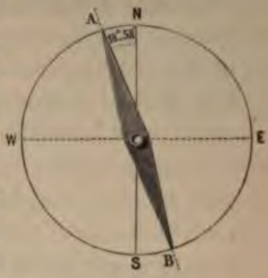

Fig. 415.—Declination

491. Inclination or Dip.—If, before magnetizing a needle, we mount it on an axis passing through its centre of gravity, and support the ends of the axis, as in Fig. 416, by a thread without torsion, the needle will remain in equilibrium in any position in which it may be placed. If it be then magnetized, it will no longer be indifferent, but will place itself in a particular vertical plane called the magnetic meridian, and will take a particular direction in this plane. This direction is not horizontal, but inclined, generally at a considerable angle, to the horizon; and this angle is called *dip* or *inclination*. Its value at Greenwich is about 67°, the end which points to the north pointing at the same time downwards. In the northern hemisphere generally, it is the north end of the needle which dips, and in the southern hemisphere it is the end which points south.

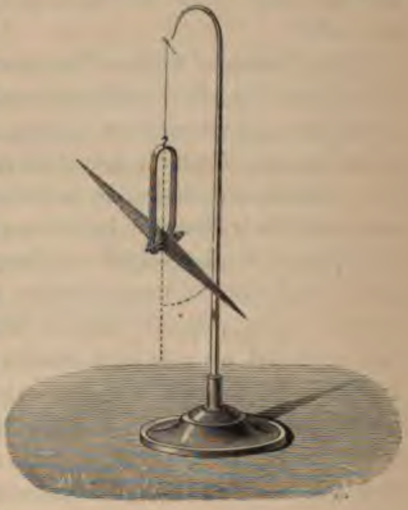

Fig. 416.—Dip.

Some readers may be glad to be reminded that by the plane of the *meridian* is meant a vertical plane passing through the place of observation, and through or parallel to the earth's axis. A horizontal line in this plane is a meridian line. The *magnetic meridian* is the vertical plane in which a magnetized needle, when freely suspended, tends to place itself.

[1] The nautical name for magnetic declination is *variation;* but it is most inconvenient and confusing to denote the element itself by the same name as the variations of the element.

It follows that, if a magnetized needle is to be balanced in a horizontal position, the point or axis of support must not be in the same vertical with the centre of gravity, but must be between the centre of gravity and the end which tends to dip. Needles thus balanced, as in the ordinary mariner's compass, are called *declination needles*.

492. Mutual Action of Poles.—On presenting one end of a magnet to one end of a needle thus balanced, we obtain either repulsion or attraction, according as the pole which is presented is similar or dissimilar to that to which it is presented. *Poles of contrary name attract each other; poles of the same name repel each other.*

This property furnishes the means of distinguishing a body which is merely magnetic (that is, capable of temporary magnetization) from a permanent magnet. The former, a piece of soft iron for example, is always attracted by either pole of a magnet; while a body which has received permanent magnetization has, in ordinary cases, two poles, of which one is attracted where the other is repelled. Magnetic attractions and repulsions are exerted without modification through any body which may be interposed, provided it be not magnetic.

492A. Names of Poles.—The phenomena of declination and inclination above described, evidently require us to regard the earth, in a broad sense, as a magnet, having one pole in the northern and the other in the southern hemisphere. Now since poles which attract one another are dissimilar, it follows that the magnetic pole of the earth which is situated in the northern hemisphere is *dissimilar* to that end of a magnetized needle which points to the north. Hence great confusion of nomenclature has arisen, the usage of the best writers being opposite to that which generally prevails. We shall call that end or pole of a needle which seeks the north, the *north-seeking* end or pole, and the other the *south-seeking* end or pole. Sir Wm. Thomson calls the north-seeking pole the *south* pole, and the other the *north* pole, because the former is similar to the south, and the latter to the north pole of the earth. In like manner most French writers call the north-seeking pole of a needle the *austral*, and the other the *boreal* pole. Popular usage in this country calls the north-seeking end the *north*, and the other the *south* pole, a nomenclature which introduces great confusion whenever we have to reason respecting the earth regarded as a magnet. Faraday, to avoid the ambiguity which has attached itself to the names north and south pole, calls the north-seeking end the *marked*, and the other the *unmarked* pole. Airy, for a similar reason, employs, in his recent *Treatise on Magnetism*, the distinctive names *red* and *blue* to denote respectively the north-seeking and south-seeking ends, these names, as well as those employed by Faraday, being purely conventional, and founded on the custom of marking the north-seeking end of a magnet with a transverse notch or a spot of red paint. Maxwell and Jenkin, in a report to the British Association,[1] call the south-seeking pole of a needle *positive*, and the north-seeking pole *negative*.

493. Magnetic Induction.—When a piece of iron is in contact with a magnet, or even when a magnet is simply brought near it, it becomes itself, for the time, a magnet, with two poles and a neutral portion between them. If we scatter filings over the iron, they will adhere to its ends, as shown in Fig. 417. If we take away the influencing magnet, the filings will fall off, and the iron will retain either no traces at all or only very faint ones of its magnetization. If we apply similar treatment to a piece of steel, we obtain a result similar in some respects, but with very important differences in degree. The steel, while under the influence of the magnet, exhibits much weaker effects than the iron; it is much more difficult to magnetize than iron, and does not admit of being so powerfully magnetized; but, on the other hand, it retains its magnetization after the influencing magnet has been withdrawn. This property of retaining magnetism when once imparted has been (somewhat awkwardly) named *coercive force*. Steel, especially when very hard, possesses great coercive force; iron, especially when very pure and soft, scarcely any.

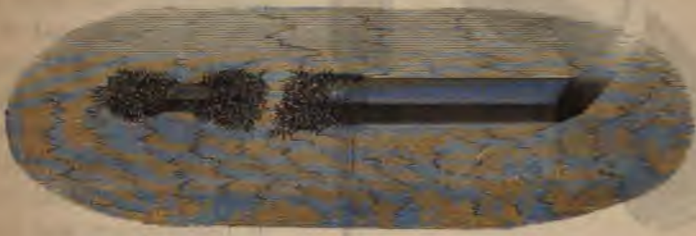

Fig. 417.—Induced Magnetism.

In magnetization by influence, which is also called *magnetic induction*, it will be found, on examination, that the pole which is next the inducing pole is of contrary name to it; and it is on account of the mutual attraction of dissimilar poles that the iron is attracted by the magnet. The iron can, in its turn, support a second piece of iron; this again can support a third, and so on through many steps. A magnetic chain can thus be formed, each of the component pieces having two poles. An action of this kind takes place in the clusters of filings which attach themselves to one end of a magnetized bar, these clusters being composed of numerous chains of filings.

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[1] *Report of Electrical Standards Committee*, Appendix C. 1863.

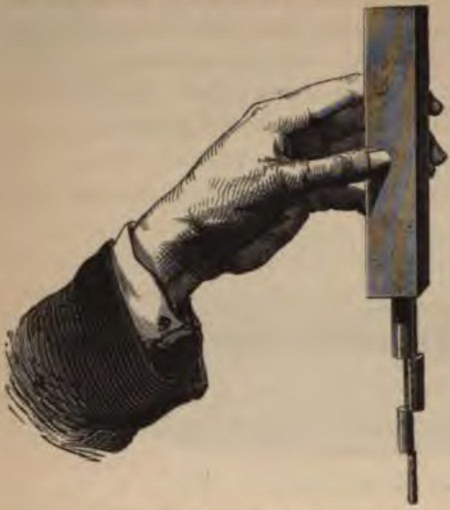

Fig. 418.—Magnetic Chain.

In comparing the phenomena of magnetic induction with those of electrical induction, we find both points of resemblance and points of difference. In the case of electricity, if the influencing and influenced body are allowed to come in contact, the former loses some of its own charge to the latter. In the case of magnetism there is no such loss, a magnet after touching soft iron is found to be as strongly magnetized as it was before.

494. Effect of Rupture on a Magnet.—If a magnet is broken into any number of pieces, every piece will be a complete magnet with poles of its own. In the case of an ordinary bar-magnet or needle, the similar poles of the pieces will all be turned the same way, as in Fig. 419, which represents a magnet AB broken into four pieces. The ends *a*, *a*, *a*, *a* are of one name, and the ends *b*, *b*, *b*, *b* of the opposite name.

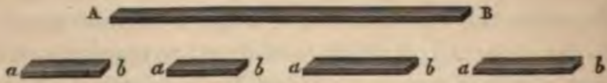

Fig. 419.—Broken Magnet.

494 A. Imaginary Magnetic Fluids: Magnetic Potential.—All mutual forces between magnets can be reduced to attractions and repulsions between different portions of two imaginary fluids,[1] one of which may be called *positive* and the other *negative.* Neither fluid can exist apart from the other; every magnet possesses equal quantities of both; quantity being measured by force of attraction or repulsion at given distance, just as in the case of electricity, like portions repelling, and unlike portions attracting each other inversely as the square of the distance. Equal quantities of the two fluids, when coexisting at the same place, produce no resultant effect, and may be regarded as destroying each other.

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[1] Poisson, following Coulomb, spoke of *two magnetic fluids*, and laid down a theory of

With reference to these imaginary fluids, *magnetic potential* can be defined in the same way as electrical potential, and magnetic *lines of force* possess the same properties as electrical lines of force (§ 445 A —445 K). The direction of magnetic force at a point can either be defined as the direction in which a pole of a magnet would be urged if brought to the point, or as the direction in which a small magnetized needle, if brought to the point and balanced at its centre of gravity, would place its line of poles; and lines of magnetic force are lines to which this direction is everywhere tangential. It is important to remark that a linear piece of soft iron, though it sets its length along a line of force, does not travel along a line of force, but deviates towards the concave side. This is easily shown by tapping the card represented in Fig. 412. It will be found that filings placed on the line $m\,m$ move along that line, and therefore at right angles to the lines of force. The force which is specified by magnetic "lines of force" is the force which *one pole* of a permanent magnet would experience; and it is the same in intensity, but opposite in direction, for dissimilar poles.

494 B. Specification of Magnetization.—A piece of steel is said to be *uniformly magnetized*, if equal and similar portions, cut in parallel directions from all parts of it, are precisely alike in their magnetic properties.

If a piece of magnetized steel be suspended at its centre of gravity, so as to be free to turn all ways about it, the effect of the earth's magnetism upon it consists in a tendency for a particular line, through this centre of gravity, to take a determinate direction, which is the direction of terrestrial magnetic force. When the line is placed in any other position, the couple tending to bring it back is propor-

their action. Sir W. Thomson, avoiding the hypothetical parts of Poisson's theory, speaks of *imaginary magnetic matter* of two dissimilar kinds. We have retained the more familiar name *fluid*, simply because it is more convenient to speak of *two fluids* than of *two kinds of matter*. It is to be noted that we cannot speak of two *magnetisms*, the name magnetism having been already appropriated in a different sense.

tional to the sine of the angle between the two positions, and is the same for all directions of deviation. The line which possesses this property is the *magnetic axis* of the body, and the name is sometimes given to all lines parallel to it. If the piece of steel be uniformly magnetized, this axis is the direction of magnetization; or *the direction of magnetization is the common direction of all those lines which tend to place themselves along lines of force* in a field[1] where the lines of force are parallel.

494 c. Ideal Simple Magnet: Thin Bar, uniformly and longitudinally Magnetized.—The mutual actions of magnets admit of very accurate expression when the magnets are very thin in comparison with their length, uniform in section, and uniformly magnetized in the direction of their length. Such bars, which may be called *simple magnets*, behave as if their forces resided solely in their ends, which may therefore in the strictest sense be called their poles. The two poles of any one such bar are equal in strength; that is to say, one of them attracts a pole of another simple magnet with the same force with which the other repels it at the same distance. In the language of the two-fluid theory, the two fluids destroy one another except at the two ends, and the quantities which reside at the ends are equal but of opposite sign. The same number which denotes the quantity of fluid at either pole, denotes the *strength of the pole*, or, as it is often called, the *strength of the magnet*. Its definition is best expressed by saying that the force between a pole of one simple magnet and a pole of another, is the product of their strengths divided by the square of the distance between them.[2]

The force which a pole of a simple magnet experiences in a magnetic field, is the *product of the strength of the pole and the intensity of the field*. This rule applies to the force which a pole experiences from the earth's magnetism, the intensity of the field being in this case the intensity of terrestrial magnetic force; and, from the uniformity of the field, the forces on the two poles are in this case equal, constituting a couple, whose arm is the line joining the poles multiplied by the sine of the angle which this line makes with the lines of force.

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[1] A *field of force* is any region of space traversed by lines of force; or, in other words, any region pervaded by force of attraction or repulsion. A *magnetic field* is any region pervaded by magnetic force. All space in the neighbourhood of the earth is a magnetic field, and within moderate distances the lines of force in it may be regarded as parallel, unless artificial magnets or pieces of iron are present to produce disturbance.

[2] We here, and throughout the remainder of this chapter, ignore the existence of induction, which, however, is not altogether absent even in the hardest steel. The effect of induction is always to favour attraction. The attractions will therefore be somewhat stronger, and the repulsions somewhat weaker, than our theory supposes.

The product of the line joining the two poles by the strength of either pole is called the *moment of the magnet*, and it is evident, from what has just been said, that the continued product of *the moment of the magnet, the intensity of terrestrial magnetic force, and the sine of the angle between the length of the magnet and the lines of force*, is equal to the moment of the couple which the earth's magnetism exerts upon the magnet.

494 D. Compound Magnet of Uniform Magnetization.—Any magnet which is not a simple magnet in the sense defined in § 494 C may be called a *compound magnet*. It is convenient to define the moment of a compound magnet by the condition stated in the concluding words of that section, so that the moments of different magnets, whether simple or compound, may be compared by comparing the couples exerted on them by terrestrial magnetism when their axes are equally inclined to the lines of force.

If a number of simple magnets of equal strength be joined end to end, with their similar poles pointing the same way, there will be mutual destruction of the two imaginary fluids at every junction, and the system will constitute one simple magnet of the same strength as any one of its components; but its moment will evidently be the sum of their moments.

If any number of simple magnets be united, either end to end or side to side, provided only that they are parallel, and have their similar poles turned the same way, the resultant couple exerted upon the whole system by terrestrial magnetism will (§ 14) be the sum of the separate couples exerted on each simple magnet, and the moment of the system will be the sum of the moments of its parts. But any piece of uniformly magnetized material may be regarded as being thus built up, and hence, if different portions be cut from the same uniformly magnetized mass, their moments will be simply proportional to their volumes. The quotient of moment by volume, for any uniformly magnetized mass, is called *intensity of magnetization*.

494 E. Actual Magnets.—The definitions and laws of simple magnets are approximately applicable to actual magnets, when magnetized in the usual manner.

If an actual bar-magnet in the form of a rectangular parallelopiped were magnetized with perfect uniformity, and in the direction of its ngth, it might be regarded as made up of a number of simple magnets laid side by side, and its behaviour would be represented by supposing a complete absence of magnetic fluid from all parts of it except its *ends* (in the strict mathematical sense). One of these terminal faces would be covered with positive, and the other with negative fluid, and if the magnet were broken across at any part of its length, the quantities of positive and negative fluid on the broken ends would be the same as on the ends of the complete magnet. The observed fact that magnets behave as if the fluids were distributed through a portion of their substance in the neighbourhood of the ends, and not confined to the ends strictly so called, indicates a falling off in magnetization towards the extremities, and is approximately represented by conceiving of a number of short magnets laid end to end, and falling off in strength towards the two extremities of the series.[1]

The resultant force due to the imaginary magnetic fluids which are distributed through the terminal portions of an actual bar-magnet is, in the case of actions at a great distance, sensibly the same as if the two portions of fluid were collected at their respective centres of gravity. These two centres of gravity are the poles of the magnet for all actions between the magnet and other magnets at a great distance, and more especially between the magnet and the earth.

The moment of any magnet, however irregular in its magnetization, may be defined by reference to the expression given in § 494C for the couple exerted on the body by terrestrial magnetism. This couple is M I *sin* α, where I denotes the intensity of terrestrial magnetic force, α the inclination of the magnetic axis of the body to the lines of the earth's magnetic force, and M the *moment* which we are defining.

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[1] Thus the last magnet at the positive end being weaker than its neighbour, its negative pole will be weaker than its neighbour's positive pole, so that there will be an excess of positive fluid at this junction. Similar reasoning applies to all the junctions near the ends. There will be an excess of positive fluid at all junctions near the positive end, and an excess of negative at all junctions near the negative end.

CHAPTER XLIV.

EXPERIMENTAL DETAILS.

495. The Earth's Force simply Directive.—The forces which produce the orientation of a magnet depend upon causes of which very little is known. They are evidently connected in some way with the earth, and are accordingly referred to TERRESTRIAL MAGNETISM. We have already stated (§ 494 B) that the combined effect of the forces exerted by terrestrial magnetism upon a magnetized needle is equivalent to a couple tending to turn the needle into a particular direction, and (§ 494 E) that in the case of needles magnetized in the ordinary way, there are two definite points or poles (near the two ends of the needle) which may be regarded as the points of application of the two equal forces which constitute the couple.

The fact that terrestrial magnetic force simply tends to turn the needle, and not to give it a movement of translation, in other words, that the resultant *force* (as distinguished from *couple*) is zero, is completely proved by the two following experiments:—

(1) If a bar of steel is weighed before and after magnetization, no change is found in its weight. This proves that the vertical component is zero.

(2) If a bar of steel, not magnetized, is suspended by a long and fine thread, the direction of the thread is of course vertical. If the bar is then magnetized, the direction of the thread still remains vertical. The most rigorous tests fail to show any change of its position. This proves that the horizontal component is zero, a conclusion which may be verified by floating a magnet on water by means of a cork. It will be found that there is no tendency to move across the water in any particular direction.

496. Horizontal, Vertical, and Total Intensities.—If S denote the strength of a magnet, and I the intensity of terrestrial magnetic force, each pole of the magnet experiences a force SI, and if L denote the distance between the poles (often called the length of the magnet), the distance between the lines of action of these two parallel and opposite forces may have any value intermediate between L and zero, according to the position in which the needle is held. It will be zero when the line of poles is that of the dipping-needle; it will be L when the line of poles is perpendicular to the dipping-needle; and will be L sin α when the line of poles is inclined at any angle α to the dipping-needle.

The force SI upon either pole of the magnet acts in the direction of the dipping-needle; in other words, in the direction of the lines of force due to terrestrial magnetism. Let δ denote the dip, that is the inclination of the lines of force to the horizon, then the force SI can be resolved into SI cos δ horizontal, and SI sin δ vertical. Hence the horizontal and vertical intensities H and V are connected with the total intensity and dip I and δ by the two equations

$$H = I \cos \delta \quad , \quad V = I \sin \delta \qquad (1)$$

which are equivalent to the following two

$$\frac{V}{H} = \tan \delta \quad , \quad V^2 + H^2 = I^2. \qquad (2)$$

497. Torsion-balance.—Coulomb, in investigating the laws of the mutual action of magnets, employed a torsion-balance scarcely differing from that which he used in his electrical researches. The suspending thread carried, at its lower end, a stirrup on which a magnetized bar was laid horizontally. The torsion-head was so adjusted that one end of the magnet was opposite the zero of the divisions on the glass case when the supporting thread was without torsion. In order to effect this adjustment, the magnet was first suspended by a thread whose torsional power was inconsiderable, so that the magnet placed itself in the magnetic meridian. The case was then turned till its zero came to this position. The torsionless thread was then replaced by a fine metallic wire, and the magnet was replaced by a copper bar of the same weight. The head was then turned till this bar came into the magnetic meridian, and lastly the magnet was put in the place of the bar.

Fig. 420 shows the arrangement adopted for observing the repulsion or attraction between one pole of the suspended magnet and one pole of another magnet placed vertically. Before the insertion of the latter, the suspended magnet was acted on by no horizontal forces except the horizontal component of terrestrial magnetism and the torsion of the wire. It was then found that the torsion requisite for keeping the magnet in any position was proportional to the sine of the displacement from the meridian.

This result is evidently in accordance with the principles stated above, for the two equal horizontal forces on the two poles being constant for all positions, the couple which they compose is proportional to the distance between their lines of action, and this distance is evidently L sin θ, L denoting the constant distance between the poles, and θ the deviation of the needle from the meridian.

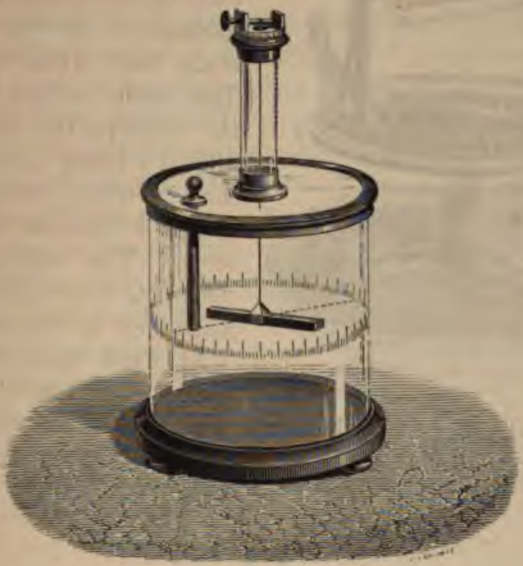

Fig. 420.—Torsion-balance.

499. Measurement of Declination.—Magnetic declination has been observed with several different forms of apparatus.

At sea, the most common method of determining it has consisted in observing the magnetic bearing of the rising or setting sun, and comparing this with its true bearing as calculated by a well-known astronomical method.

For more accurate determination on land, the declination compass or declination theodolite[1] (Fig. 422) has been frequently employed.

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[1] A *theodolite* consists of a telescope mounted so as to have independent motions in

When the instrument is set by the help of astronomical observations, so that the vertical plane in which the telescope LL′ (or more accurately its line of collimation) moves, coincides with the geographical meridian, the ends of the needle indicate the declination on the graduated circle over which they move. This circle in fact turns with the telescope, the line of 0° and 180° *ns* being always in the same vertical plane with the line of collimation of the telescope. The external divided circle PQ is used for setting the instrument in the meridian.

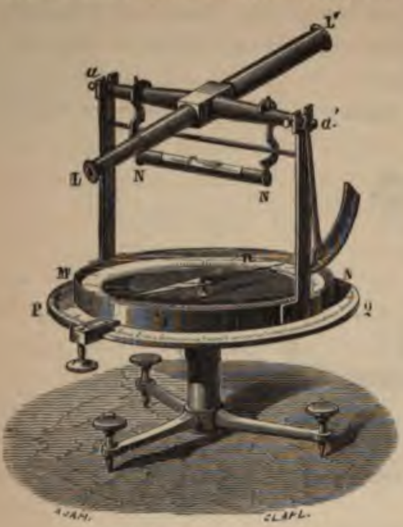

Fig. 422.—Declination Theodolite.

At fixed observatories more accurate methods of observation are employed. Fig. 422A shows the arrangement adopted at Greenwich. A bar-magnet B carries at one end a cross of fine threads C, and

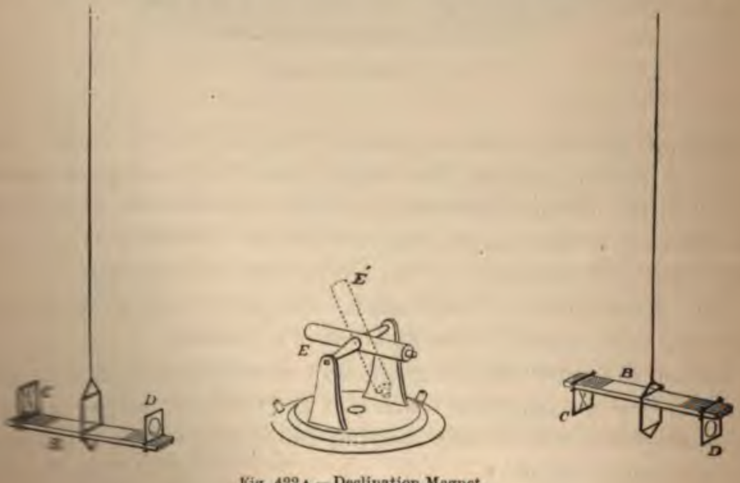

Fig. 422A.—Declination Magnet.

[illegible] altitude, the amounts of these motions being indicated by divided circles or [illegible]. It does not differ essentially from the larger instrument called the [illegible] at the other a lens D, the distance between them being equal to the focal length of the lens, thus forming a kind of inverted telescope, whose line of collimation is the line joining the cross to the optical centre of the lens. The bar is suspended by means of a stirrup from a torsionless thread, and sets its magnetic axis in the magnetic meridian. The telescope E, with theodolite mounting, is stationed opposite the end which carries the lens, and is so adjusted at each observation that its line of collimation is parallel to that of the inverted telescope carried by the magnet, an adjustment which is identified by seeing the cross C coincident with a similar cross fixed in the interior of the telescope E. When the observation has been made with the magnet in one position, it must be repeated with the magnet turned upside down as shown in the figure. Error of parallelism between the magnetic axis of the bar and the line of collimation of the inverted telescope which it carries, will affect these two observations to the same extent in opposite directions, and will therefore disappear from their mean. The readings are taken on a horizontal circle corresponding to the outer circle in Fig. 422, and astronomical observations must be made once for all to determine what reading corresponds to the geographical meridian.

Another very accurate method consists in rigidly attaching to the bar, instead of the lens and cross, a small vertical mirror. This can either be viewed through a telescope, so as to show the reflection of a horizontal scale of equal parts, which will appear to travel across the field of view of the telescope as the magnet turns, or it can be employed to throw the image of a spot of light either upon a screen viewed by the observer, or still better upon photographic paper drawn by clock-work, which leaves a permanent record of continuous changes. Both these methods of employing mirrors for the observation of small movements of rotation are now extensively employed in many applications. They appear to have been first introduced by Gauss, who employed them for the purpose which we are now considering.

500. Measurement of Dip.—The dip-circle or inclination compass is represented in Fig. 423. It consists essentially of a magnetized needle, very accurately and delicately mounted on a horizontal axis through its centre of gravity, in the centre of a vertical circle on which the positions of the two ends of the needle can be read off. This circle can be turned with the needle into any azimuth, the amount of rotation being indicated by a horizontal circle. It is obvious that, if the vertical circle is placed in the plane of the magnetic meridian, the needle, being free to move in this plane, will directly indicate the dip. On the other hand, if the vertical circle is placed in a plane perpendicular to the magnetic meridian, the horizontal component of terrestrial magnetism is prevented from moving the needle, which, accordingly, obeys the vertical component only, and takes a vertical position. In intermediate positions of the vertical circle, the needle will assume positions intermediate between the vertical and the true angle of dip. In fact, if θ be the angle which the plane of the vertical circle makes with the magnetic meridian, the component H sin θ of terrestrial magnetism, being perpendicular to this plane, merely tends to produce pressure against the supports, and the horizontal component influencing the position of the needle is only H cos θ, which lies in the plane of the circle. As none of the vertical force is destroyed, the tangent of the apparent dip will be $\frac{V}{H\cos\theta}=\frac{\tan\delta}{\cos\theta}$. The most accurate method of setting the vertical circle in the magnetic meridian consists in first adjusting it so that the needle takes a vertical position, and then turning it through 90°.

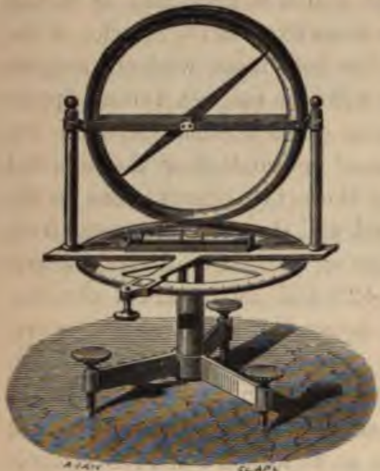

Fig. 423.—Dip-circle.

The instrument having thus been set, and a reading taken at each end of the needle, it should be turned in azimuth through 180°, and another pair of readings taken. By employing the mean of these two pairs of readings, several sources of error are eliminated, including non-coincidence of the axis of magnetization with the line joining the ends of the needle. One important source of error—deviation of the centre of gravity from the axis of suspension in a direction parallel to the length of the needle, is, however, not thus corrected. It can only be eliminated by remagnetizing the needle in the reverse direction so as to interchange its poles. The mean of the results obtained before and after the reversal of its magnetization will be the true dip.

A better form of instrument, known as the Kew dip-circle, is now employed. Its essential parts are represented in Fig. 423 A. There is no metal near the needle, and the readings are taken on a circle round which two telescopes travel. In each observation the telescopes are directed to the two ends of the needle.

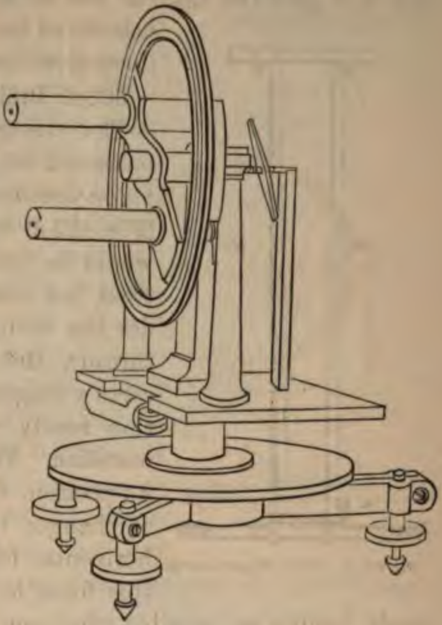

Fig. 423 A.—Kew Dip-circle.

500 A. Measurement of Intensity of Terrestrial Magnetic Force.—The complete specification of the earth's magnetic force at any place involves three independent elements. For example, if declination, dip, and horizontal force are determined by observation, vertical force and total force can be calculated by the formulæ of § 496.

Observations of magnetic force are made either by counting the number of vibrations executed in a given time, or by statical measurements. If a magnet executes small horizontal vibrations under the influence of the earth's magnetism, the square of the number of vibrations in a given time is proportional to $\frac{\mathrm{H\,M}}{\mu}$, H denoting the horizontal intensity, M the moment of the magnet, and μ its moment of inertia about the centre of suspension. Hence it is easy to observe the *variations* of horizontal intensity which occur from time to time, if we can insure that our magnet itself shall undergo no change, or if we have the means of correcting for such changes as it undergoes. To obtain absolute determinations of horizontal intensity, the following method is employed.

First, observe the time of vibration of a freely-suspended horizontal magnet under the influence of the earth alone,—this will give the *product* of the earth's horizontal intensity and the moment of the magnet.

Secondly, employ this same magnet to act upon another also freely suspended, and thus compare its influence with that of the earth,—this will give the ratio of the same two quantities whose product was found before. Hence the two quantities themselves can easily be computed.

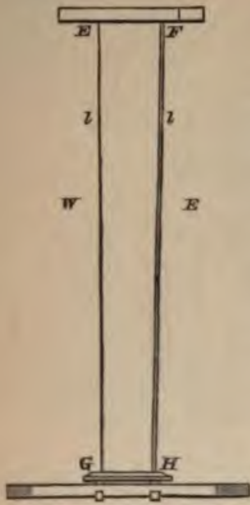

Fig. 423 B.—Bifilar Magnetometer.

500 B. Bifilar and Balance Magnetometers.—The changes of horizontal intensity are measured statically by means of the *bifilar magnetometer*. This consists of a bar-magnet (Fig. 423 B) suspended by two threads, which would be parallel if the bar were unmagnetized, but matters are so arranged that, under the combined action of the pull of the threads, the weight of the bar, and the earth's magnetism, the bar is kept in a position nearly perpendicular to the magnetic meridian. The only changes which occur in its position from time to time are those due to changes in the *intensity* of the earth's horizontal force, changes in the direction of this force, to the extent of a few minutes of angle, having no sensible effect, on account of the near approach to perpendicularity.

The changes of vertical intensity are measured by the *balance-magnetometer*, which consists of a bar-magnet placed in the magnetic meridian and suspended on knife-edges like the beam of an ordinary balance. Its deviations from horizontality are measures of the changes of vertical intensity.

Both these instruments have mirrors attached to the magnet, which produce a photographic record of the movements of the magnet, on principles above explained.

The moment of a magnet varies with temperature, being diminished by something like one ten-thousandth part of itself for each degree Fahr. of increase, and increasing again at the same rate when the temperature falls. Hence magnetic observatories must be kept at a nearly uniform temperature. They must also be completely free from iron. No iron nails are allowed to be used in their construction, copper being employed instead.

500 C. Results of Observation.—The annexed figures[1] contain an

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[1] For Figs. 422 A, 423 A, B, C, D, we are indebted to the publishers of Airy's *Treatise on Magnetism.*

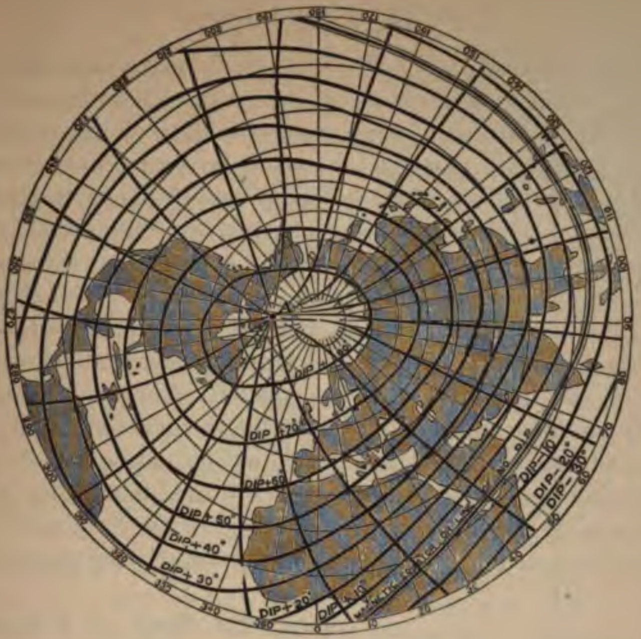

Fig. 423 c.—Northern Hemisphere.

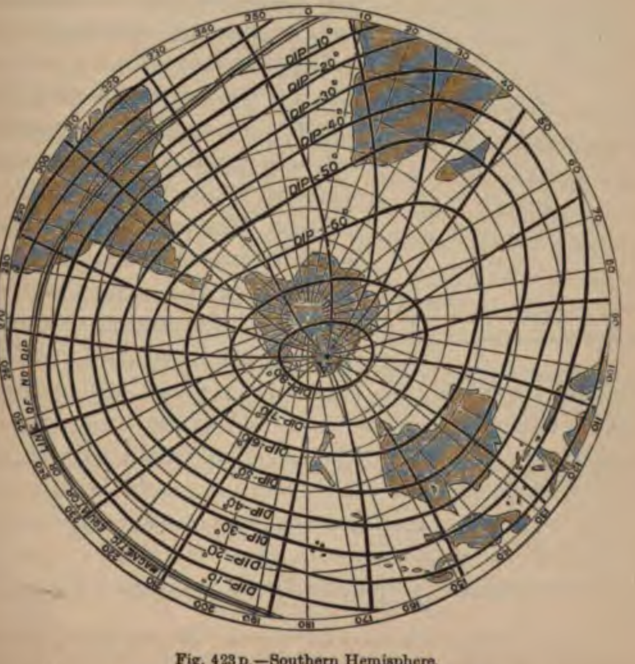

Fig. 423 d.—Southern Hemisphere.

Magnetic Meridians and Lines of Equal Dip.

approximate representation of the magnetic meridians and lines of equal dip over both hemispheres of the earth. These two systems of lines combined, furnish a complete specification of the *direction* of magnetic force at all parts of the earth's surface; but they indicate nothing as to *intensity*. The curves of equal total intensity have a general resemblance to the lines of equal dip, the intensity being greatest near the poles, and least near the equator; but their arrangement is somewhat more complicated, there being two north poles of greatest intensity, one in Canada, and the other in the northern part of Siberia. Speaking roughly, the intensity near the poles is about double of the intensity near the equator. Curves of equal total intensity are often called *isodynamic* lines; curves of equal dip are often called *isoclinic* lines; curves of equal declination are often called *isogonic* lines; curves cutting the magnetic meridians at right angles are often called *magnetic parallels*. They are the lines which would be traced by continually travelling in the direction of magnetic east or west.

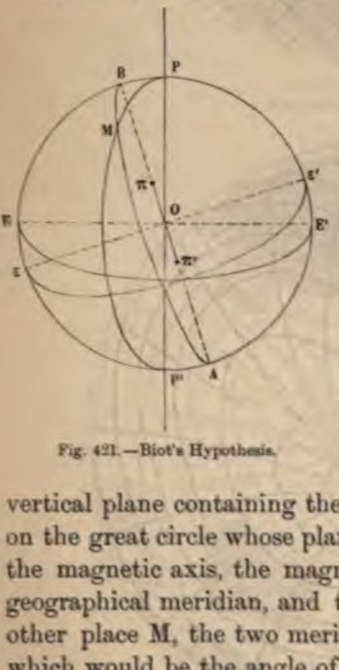

Fig. 421.—Biot's Hypothesis.

500 D. The Earth as a Magnet.[1]—The intensity and direction of terrestrial magnetic force at different places may be *roughly* represented by supposing that there is a magnet $\pi\pi'$ (Fig. 421) at the earth's centre, having a length very small in comparison with the earth's radius, and making an angle of about 20° with the earth's axis of rotation. The points A and B obtained by producing this magnet longitudinally to meet the surface, would be the magnetic poles, and at any other place the magnetic meridian would be the vertical plane containing the magnetic axis A B. At places situated on the great circle whose plane contains both the axis of rotation and the magnetic axis, the magnetic meridian would coincide with the geographical meridian, and the declination would be zero. At any other place M, the two meridians would cut each other at an angle which would be the angle of declination. At all places on the great circle $\epsilon\epsilon'$ whose plane is perpendicular to the magnetic axis, a needle suspended at its centre of gravity would place itself parallel to this axis, and consequently the dip would be zero. This circle would be the magnetic equator.[1] It would cut the geographical equator at an angle of 20°. Proceeding from the magnetic equator towards the north magnetic pole B, the needle would dip more and more, until at B it became vertical. A declination needle at B would remain indifferently in all positions. Similar phenomena would be observed at the other magnetic pole A. The end of the needle which would dip at B, and which at other parts of the earth would point to magnetic north, is that which is similar to the southern pole π' of the terrestrial magnet $\pi\pi'$, and the pole which is similar to π would dip at A.

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[1] This section corresponds to § 498 in the original. The hypothesis which it describes is known as *Biot's hypothesis*.

The actual phenomena of terrestrial magnetism are not in very close agreement with the results which would follow from the presence of such a magnet as we have described in the earth's interior, nor do they agree well with the hypothesis of two interior magnets inclined at an angle to each other, which has also been proposed. It would rather appear that the earth's magnetism is distributed in a manner not reducible to any simple expression.

501. Changes of Declination and Dip.—Declination and dip vary greatly not only from place to place, but also from time to time. Thus at the date of the earliest recorded observations at Paris, 1580, the declination was about 11° 30′ E. In 1663 the needle pointed due north and south, so that Paris was on the line of no declination. Since that time the declination has been west, increasing to a maximum of 22° 34′, which it attained in 1814. Since then it has gone on diminishing to the present time, its present value being about 19° W.

As to dip, its amount at Paris has continued to diminish ever since it was first observed in 1671. From 75° it has fallen to 66°, its present value. As its variations since 1863 have been scarcely sensible, it would seem to have now attained a minimum, to be followed by a gradual increase.

501 A. Magnetic Storms.—Besides the gradual changes which occur in terrestrial magnetism, both as regards direction and intensity of force, in the course of long periods of time, there are minute fluctua-

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[1] If latitude reckoned from the magnetic equator be called magnetic latitude, and denoted by λ, it can be shown that we should have, on this theory,

$$\tan\delta = 2\tan\lambda\ ;\ I = E\sqrt{\cos^2\lambda + 4\sin^2\lambda},$$

E denoting the intensity at the magnetic equator.

tions continually traceable. To a certain extent these are dependent on the varying position of the sun, and, to a much smaller extent, of the moon, with respect to the place of observation; but over and above all regular and periodic changes, there is a large amount of irregular fluctuation, which occasionally becomes so great as to constitute what is called a *magnetic storm*. Magnetic storms "are not connected with thunder-storms, or any other known disturbance of the atmosphere; but they are invariably connected with exhibitions of aurora borealis, and with spontaneous galvanic currents in the ordinary telegraph wires; and this connection is found to be so certain, that, upon remarking the display of one of the three classes of phenomena, we can at once assert that the other two are observable (the aurora borealis sometimes not visible here, but certainly visible in a more northern latitude)."[1] They are sensibly the same at stations many miles apart, for example at Greenwich and Kew, and they affect the direction and amount of horizontal much more than of vertical force.

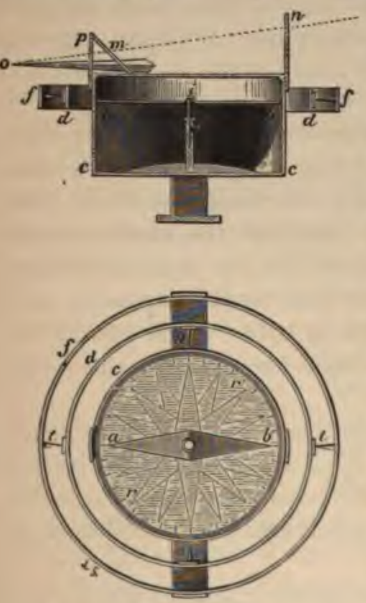

Fig. 424.—Ship's Compass.

502. Ship's Compass.—In a ship's compass, the box *cc* which contains the needle is weighted below, and hung on gimbals, which consist of two rings so arranged as to admit of motion about two independent horizontal axes *t t*, *u u* at right angles to each other. This arrangement prevents it from being tilted by the pitching and rolling of the ship. The needle *ab* is firmly attached to the compass-card, which is a circular card marked with the 32 points of the compass, as in Fig. 425, and also usually divided at its circumference into 360 degrees. The card with its attached needle is accurately balanced on a point at its centre. The needle, which, in actual use, is concealed from view, lies along the line N S. The box contains a vertical mark in its interior on the side next the ship's bow; and this mark serves as an index for reading off on the card the direction to which the ship's head is turned. Sometimes a reflector is employed, as *m* in the first figure, in such a position that an observer looking in from behind can read off the indicated direction by reflection, and can at the same time sight a distant object whose magnetic bearing is required. The origin of the compass is very obscure. The ancients were aware that the loadstone attracted iron, but were ignorant of its directing property. The instrument came into use in Europe some time in the course of the thirteenth century.

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[1] Airy on *Magnetism*, p. 204.

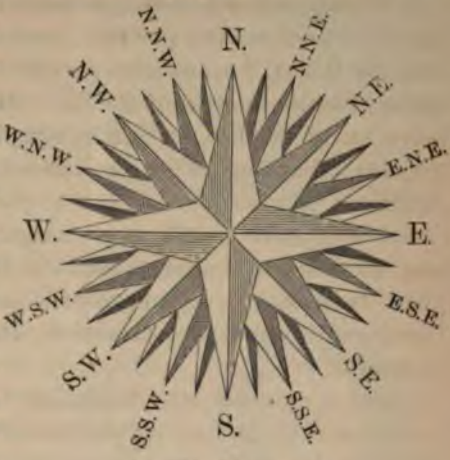

Fig. 425.—Compass-card.

503. Methods of Magnetization.—The usual process of magnetizing a bar consists in rubbing it with or against a bar already magnetized. Different methods of doing this, called single touch, double touch, &c., have been devised, in which magnetized bars of steel were the magnetizing agents. Much greater power can, however, be obtained by means of electro-magnetism; and the two following methods are now almost exclusively employed by the makers of magnets.

1. A fixed electro-magnet (Fig. 427) is employed, and the bar to be magnetized is drawn in opposite directions over its two poles. Each stroke tends to develop at the end of the bar at which the motion ceases, the opposite magnetism to that of the pole which is

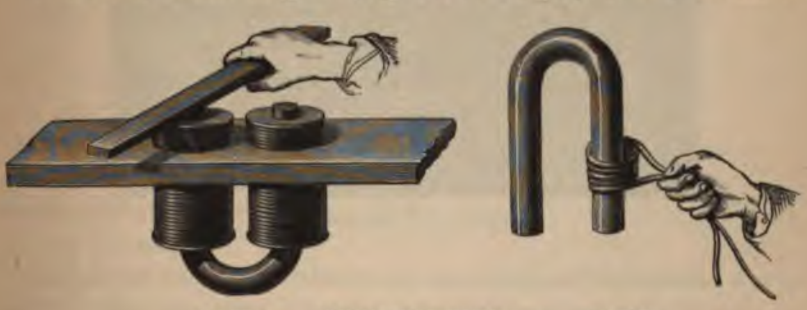

Fig. 427. Methods of Magnetization. Fig. 428.

in contact with it. Hence strokes in opposite directions over the two contrary poles tend to magnetize the bar the same way.

2. When very intense magnetization is to be produced, the electromagnet must be very powerful, and the bar then adheres to it so strongly that the operation above described becomes difficult of execution, besides scratching the bar. Hence it is more convenient to move along the bar, as in Fig. 428, a coil of wire through which a current is passing. This was the method employed by Arago and Ampère.

A bar of steel is said to be magnetized to *saturation*, when its magnetization is as intense as it is able to retain without sensible loss. It is possible, by means of a powerful magnet, to magnetize a bar considerably above saturation; but in this case it rapidly loses intensity.

Pieces of iron and steel frequently become magnetized temporarily or permanently by the influence of the earth's magnetism, and this action is the more powerful as the direction of their length more nearly coincides with that of the dipping-needle. If fire-irons which have usually stood in a nearly vertical position be examined by their influence on a needle, they will generally be found to have acquired some permanent magnetism, the lower end being that which seeks the north.

It sometimes happens that, either from some peculiarity in the structure of a bar, or from some irregularity in the magnetizing process, a reversal of the direction of magnetization occurs in some part or parts of the length as compared with the rest. In this case the magnet will have not only a pole at each end, but also a pole at each point where the reversal occurs. These intermediate poles are called *consequent points.* Fig. 429 represents the arrangement of iron-filings about a bar-magnet which has two consequent points a', b'.

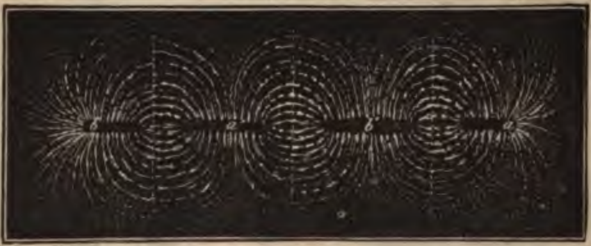

Fig. 429.—Consequent Points.

The whole bar may be regarded as consisting of three magnets laid end to end, the ends which are in contact being similar poles. Thus the two poles at a' and the one pole at a are of one kind, while the two poles at b' and the one pole at b are of the opposite kind.

The lifting power (or *portative* force) of a magnet generally increases with its size, but not in simple proportion, small magnets being usually able to sustain a greater multiple of their own weight than large ones. Hence it has been found advantageous to construct compound magnets, consisting of a number of thin bars laid side by side, with their similar poles all pointing the same way. Fig. 430 represents such a compound magnet composed of twelve elementary bars, arranged 4 × 3. Their ends are inserted in masses of soft iron, the extremities of which constitute the poles of the system.

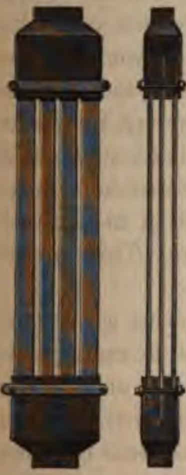
Fig 430.—Compound Magnet.

Fig. 431 represents a compound horse-shoe magnet, whose poles N and S support a keeper of soft iron, from which is hung a bucket for holding weights. By continually adding fresh weights day after day, the magnet may be made to carry a much greater load than it could have supported originally; but if the keeper is torn away from the magnet, the additional power is instantly lost, and the magnet is only able to sustain its original load.

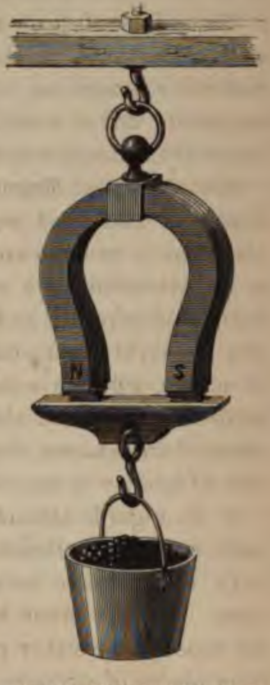

Fig. 431.—Compound Horse-shoe Magnet.

Much attention was at one time given to methods of obtaining steel magnets of great power. These researches have now been superseded by electro-magnetism, which affords the means of obtaining temporary magnets of almost any power we please.

503 A. Molecular Changes accompanying Magnetization.—Joule has shown that, when a bar of iron is magnetized longitudinally, it acquires a slight increase of length, compensated, however, by transverse contraction, so that its volume undergoes no change.

If the magnetization is effected suddenly, by completing an electric circuit, an ear close to the bar hears a clink, and another clink is heard when the current is stopped.

These phenomena have been accounted for by the hypothesis that, when iron is magnetized, its molecules place their longest dimensions in the direction of magnetization.

The effect of heat in diminishing the strength of a magnet is another instance of the connection between magnetism and other molecular conditions. In ordinary cases, this diminution is merely transient; but if a steel magnet is raised to a white-heat, it is permanently demagnetized.

504. Action of Magnetism on all Bodies.—It has long been known that iron and steel were not the only substances which could be acted on by magnetism. Nickel and cobalt especially were known to be attracted by a magnet, though very much more feebly than iron, while bismuth and antimony were repelled. Faraday, by means of a powerful electro-magnet, showed that all or nearly all substances in nature, whether solid, liquid, or gaseous, were susceptible of magnetic influence, and that they could all be arranged in one or the other of two classes, characterized by opposite qualities. This opposition of quality is manifested in two ways.

1. As regards attraction and repulsion, iron and other *paramagnetic* bodies are attracted by either pole of a magnet, or more generally, they tend to move from places of weaker to places of stronger force. On the other hand, bismuth and other *diamagnetic* bodies are repelled by either pole of a magnet, and in general tend to move from places of stronger to places of weaker force.

2. As regards orientation, a paramagnetic body when suspended between the poles of a magnet tends to set *axially;* that is to say, tends to place its length along the line joining the poles, or more generally, when placed in any magnetic field, tends to place its length along the lines of force. Hence the name *para*magnetic.[1] A *dia*magnetic body, on the other hand, when suspended between the poles, sets *equatorially;* that is to say, places its length at right angles to

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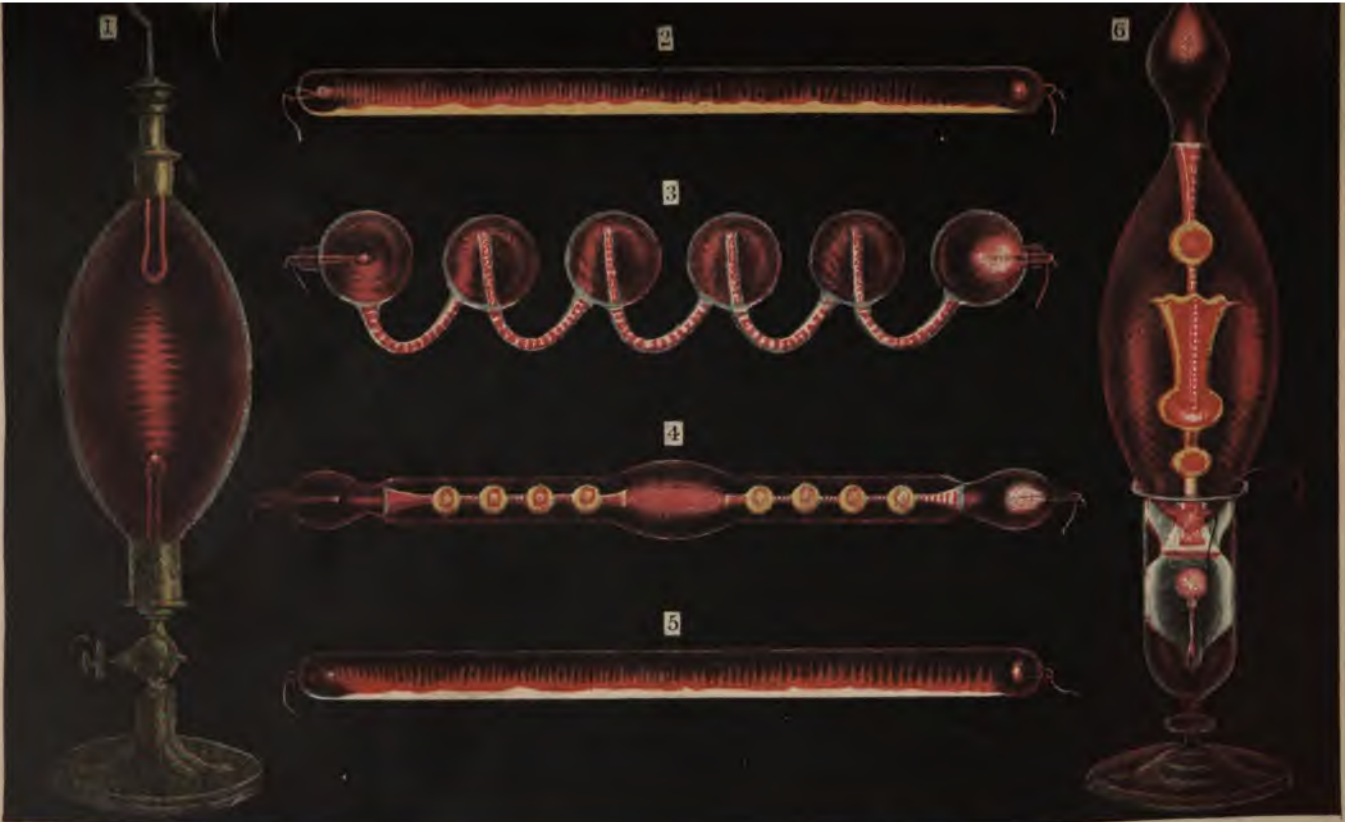
[1] The nomenclature here adopted was proposed by Faraday in 1850 (*Researches*, § 2790), and is eminently worthy of acceptance. Many writers, however, continue to employ *magnetic* in the exclusive sense of *para*magnetic. To be consistent, they should call the other class *anti*magnetic, not *dia*magnetic. "The word *magnetic* ought to be general, and include *all* the phenomena and effects produced by the power."



ELECTRIC DISCHARGE IN RAREFIED GASES.

1. *Discharge in Vapour of Alcohol.* (2.3.4.5. *Geissler's Tubes enclosing rarefied Gases*) 2. *Shows the Fluorescence of Sulphuret of Calcium.* 4. *Fluorescence of Uranium glass.*
5. *Fluorescence of Sulphuret of Strontium.* 6. *Fluorescence of Uranium glass and of Sulphate of Quinine.*

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the line joining the poles, or, more generally, tends to place its length at right angles to magnetic lines of force.

Fig. 432 represents the apparatus commonly employed for experiments on this subject. B, B are two large coils of stout copper wire, wound on massive hollow cylinders of soft iron. These latter form portions of the heavy frames F, F, which can be slid to or from each other, and fixed firmly at any distance by means of the screws E, E.

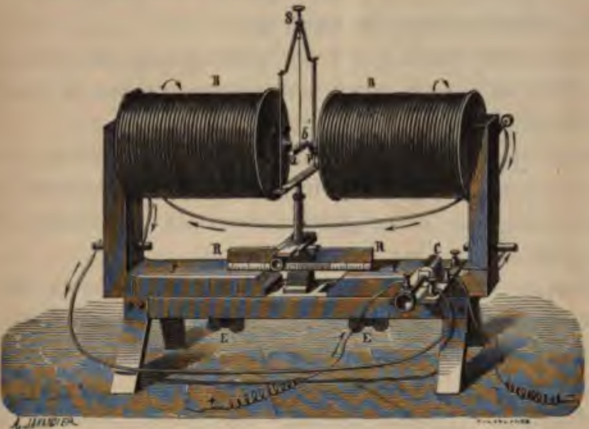

Fig. 432.—Apparatus for Diamagnetism.

The armatures P, which can be screwed on or off, have the form of rounded cones, and produce a great concentration of force at their extremities.

The action of magnetism upon a solid can be examined by suspending a small bar of it *a b*, by means of a special support RS, between the poles P. When a current is passed through the coils, the bar immediately exhibits a preference either for the axial or the equatorial position. Attraction and repulsion are most easily tested by suspending a small ball of the substance at the level of the central line of poles, but a little beside it, the poles having first been brought very near together. On passing the current through the coil, the ball will move inwards towards the line of poles if paramagnetic, and outwards if diamagnetic.

It is important, however, to remark, that experiments of this kind, unless performed *in vacuo*, are merely differential—they merely indicate that the suspended body is, in the one case, more paramagnetic or less diamagnetic; in the other case more diamagnetic or less paramagnetic, than the medium in which it moves, the comparison being made between equal volumes. Oxygen is paramagnetic, and nitrogen is nearly or quite indifferent. Air is accordingly paramagnetic, and a body suspended in air appears less paramagnetic or more diamagnetic than it really is. If more feebly paramagnetic than air, it will appear to be diamagnetic. Thus heated air, in consequence probably of its rarefaction, appears diamagnetic when surrounded by cold air, and the flame of a taper is repelled downwards and outwards from the axial line.

If, on the other hand, the body under examination is suspended in water, it will appear more paramagnetic than it really is, by reason of the diamagnetism of water.

The following metals are paramagnetic: iron, nickel, cobalt, manganese, chromium, titanium, cerium, palladium, platinum, osmium.

The following are diamagnetic: bismuth, antimony, lead, tin, mercury, gold, silver, zinc, copper.

The following substances are also diamagnetic: water, alcohol, flint glass, phosphorus, sulphur, resin, wax, sugar, starch, wood, ivory, beef (whether fresh or dried), blood (whether fresh or dried), leather, apple, bread.

504A. Magneto-crystallic Action.—The orientation of crystals in a magnetic field presents some remarkable peculiarities, which were extremely perplexing to investigators until Tyndall and Knoblauch discovered the principle on which they depend. This principle is, that crystals are susceptible of magnetic induction to different degrees in different directions. Every crystal (except those belonging to the cubic system) has either one line or one plane along which induction takes place more powerfully than in any other direction; and it is this line or plane which tends to place itself axially or equatorially according as the crystal is paramagnetic or diamagnetic. The directions of most powerful and least powerful induction are found to be closely related to the optic axes of crystals, and also to their planes of cleavage. When a sphere cut from a crystal is brought near to one pole of a magnet, it is attracted or repelled (according as it is para- or dia-magnetic) with the greatest force when the direction of most powerful induction coincides with the direction of the force.

Directions of unequal induction can be produced artificially in non-crystalline substances by applying pressure. "Bismuth is a brittle metal, and can readily be reduced to a fine powder in a mortar. Let a tea-spoonful of the powdered metal be wetted with gum-water, kneaded into a paste, and made into a little roll, say an inch long and a quarter of an inch across. Hung between the excited poles, it will set itself like a little bar of bismuth—equatorial. Place the roll, protected by bits of pasteboard, within the jaws of a vice, squeeze it flat, and suspend the plate thus formed between the poles. On exciting the magnet, the plate will turn, with the energy of a magnetic substance, into the axial position, though its length may be ten times its breadth.

"Pound a piece of carbonate of iron into fine powder, and form it into a roll in the manner described. Hung between the excited poles, it will stand as an ordinary [para]magnetic substance—axial. Squeeze it in the vice, and suspend it edgeways, its position will be immediately reversed. On the development of the magnetic force, the plate thus formed will recoil from the poles, *as if violently repelled*, and take up the equatorial position."[1]

In these experiments the direction of most powerful induction is a line transverse to the thickness, and this is also the direction in which pressure has been applied. Tyndall accordingly concludes that "if the arrangement of the component particles of any body be such as to present different degrees of proximity in different directions, then the line of closest proximity, other circumstances being equal, will be that chosen by the respective forces for the exhibition of their greatest energy. If the mass be [para]magnetic, this line will stand axial; if diamagnetic, equatorial."[2]

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[1] Tyndall on *Diamagnetism*, p. 18.

[2] Ibid. p. 23.

CURRENT ELECTRICITY.

CHAPTER XLV.

GALVANIC BATTERY.

505. Voltaic Electricity.—Towards the close of last century, when the discovery of the various phenomena of frictional electricity had been followed by Coulomb's investigations, which first reduced them to an accurate theory, a new instrument was brought to light destined to effect a complete revolution in electrical science. In place of an element difficult to manage, capricious and uncertain in its behaviour, and constantly baffling investigation by the rapidity of its dissipation, the galvanic battery furnished a steady source of electricity, constantly available in all weathers, and requiring no special precautions to prevent its escape. Moreover, the electricity thus developed exhibited an entirely new set of phenomena, and opened up the way to such various and important applications, that frictional electricity at once fell into the second place, and the new agent became the main object of interest with all electrical investigators.

506. Galvanic Element.—The source of this new form of electricity is chemical action.

When a metal which is easily attacked by an acid is immersed in the acid, (for example, zinc in dilute sulphuric acid,) difference of potential is immediately established between them at the surface of contact, the acid becoming positive with respect to the metal. If either the acid or the metal is insulated (except where they touch each other) this difference of potential prevents chemical action from taking place, at least when the metal is quite pure and homogeneous. If, however, connection be established between the zinc and the acid by means of a conductor (such as platinum) which is not liable to be attacked by the acid, a continual current will flow through this conductor in a direction tending to diminish the difference of potential, and continual chemical action will take place between the acid and the zinc.

Such an arrangement constitutes a galvanic or voltaic *element* or *cell*, and the difference of potential which exists between the acid and the zinc at the surface of contact is called the *electro-motive force* of the element. This difference appears to be the same when the current is flowing as when it is prevented from flowing by insulation.

If, instead of platinum, we establish the connection by means of a metal such as copper, which is liable to be acted on by the acid, but in a much lower degree than zinc, there is probably a slight excess of potential in the acid above the copper, and the electro-motive force of the element is diminished by this difference of potential. In every case, the electro-motive force is the difference between the potentials of the two metals when both are immersed wholly or partially in the acid, and are otherwise insulated.

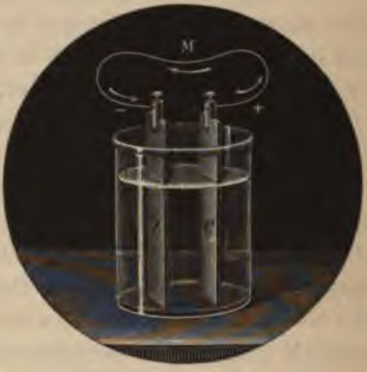

Fig. 433.—Voltaic Element.

Fig. 433 represents one of the simplest forms of such an arrangement,—a zinc and copper cell. Two plates Z, C, one of zinc, and the other of copper, are partially immersed in water acidulated by the addition of sulphuric acid, and are connected by means of a wire M, and binding-screws. The direction of the current through this wire is from higher to lower potential, and therefore from the copper to the zinc plate. An equal current flows through the acidulated water from the surface of contact with the zinc to the plate of copper. The chemical action which takes place at the surface of the zinc plate, furnishes, as long as it lasts, a continual supply of positive electricity to the acid and of negative electricity to the zinc. These opposite electricities cannot unite at the surface where they are produced, such union being prevented by the chemical relations which produced them, and therefore flow round to meet each other through the circuit composed of acid, copper plate, wire, and zinc plate. For the sake of brevity, the direction in which the positive electricity flows is always spoken of as the *direction of the current.*

508. Galvanic Battery.—By connecting the plates of successive elements in the manner represented in Fig. 434, we obtain a battery. The copper of the first cell on the left hand is connected with the zinc of the second, the copper of the second with the zinc of the third, and so on to the end of the series. The zinc of the first and the copper of the last cell (or wires proceeding from them) constitute the *electrodes* or *poles* of the battery, the zinc being the negative, and the copper the positive electrode. When these are insulated from each other, each copper is at the same potential[1] as the zinc of the next cell with which it is connected, and there is a sudden rise of potential in passing from each zinc to the liquid in contact with it. This rise occurs in four places in the arrangement represented in the figure, so that there are five distinct values of potential in different parts of the system. The highest value is for the copper on the extreme right, and the lowest is for the zinc on the extreme left, the difference between their values being four times as great as a single cell would give. This fact is usually expressed by saying that the electro-motive force of a battery of n similar cells arranged in series is n times the electro-motive force of a single cell. When the electrodes are connected, the current flows through the connecting wire from the positive electrode (copper) to the negative electrode (zinc).

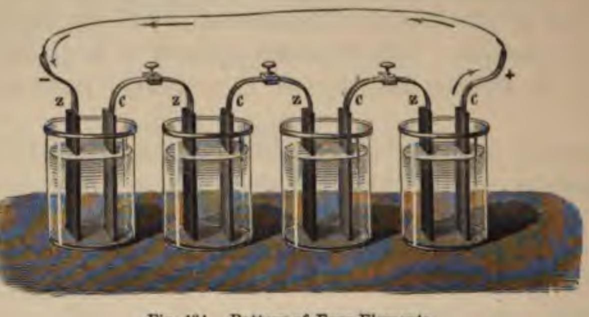

Fig. 434.—Battery of Four Elements.

509. Galvani's Discoveries.—About the year 1780, Galvani, professor of anatomy at Bologna, had his attention called to the circumstance that some recently skinned frogs, lying on a table near an electrical machine, moved as if alive, on sparks being drawn from the machine.

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[1] We neglect here, as relatively insignificant, the small difference of potential which probably always exists between two dissimilar metals in contact.

Struck with the apparent connection thus manifested between electricity and vital action, he commenced a series of experiments on the effects of electricity upon the animal system. In the course of these experiments, it so happened that, on one occasion, several dead frogs were hung on an iron balcony by means of copper hooks which were in contact with the lumbar nerves, and the legs of some of them were observed to move convulsively. He succeeded in obtaining a repetition of these movements by placing one of the frogs on a plate of iron, and touching the lumbar nerves with one end of a copper wire, the other end of which was in contact with the iron plate. Another mode of obtaining the result is represented in Fig. 435, two wires of different metals being employed which touch each other at one end, while their other ends touch respectively the lumbar nerves and the crural muscles. Every time the contact is completed, the limb is convulsed.

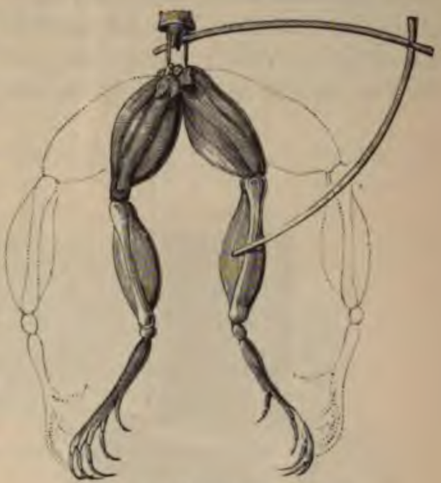

Fig. 435.—Experiment with Frog.

Galvani's explanation was, that at the junction of the nerves and muscles there is a separation of the two electricities, the nerve being positively, and the muscle negatively electrified, and that the convulsive movements are due to the establishment of communication between these two electricities by means of the connecting metals.

Volta, professor of physics at Pavia, disproved this explanation by showing that the movements could be produced by merely connecting two parts of a muscle by means of an arc of two metals; and he referred the source of electricity not to the junction of nerve and muscle, but to the junction of the two metals. Acting on this belief, he constructed in the year 1800 a voltaic pile.

511. Voltaic Pile.—This consisted of a series of discs of copper, zinc, and wet cloth, *c*, *z*, *d*, Fig. 436, arranged in uniform order, thus—copper, zinc, cloth, copper, zinc, cloth . . . the lowest plate of all being copper and the highest zinc. The wet cloth was intended merely to serve as a conductor, and prevent contact between each zinc and the copper above it. All the contacts between zinc and copper were between a copper below and a zinc above, so that they all tended, according to Volta's theory, to produce a current of electricity in the same direction. The effects obtained from the pile were so powerful as to excite extraordinary interest in the scientific world.

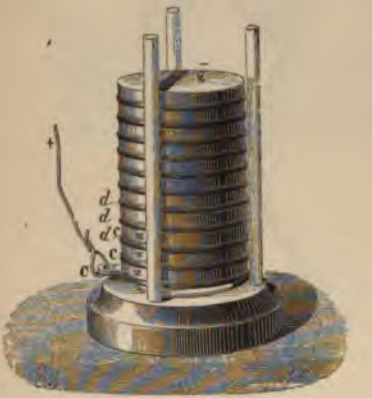

Fig. 436.—Structure of Pile.

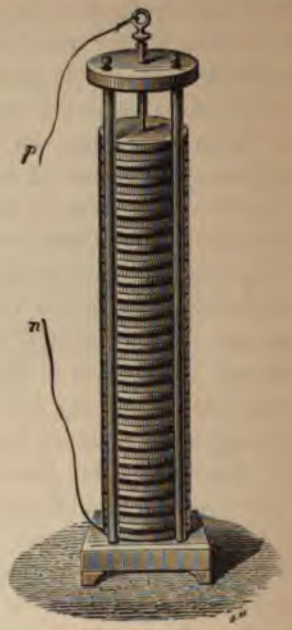

Fig. 437.—Complete Pile.

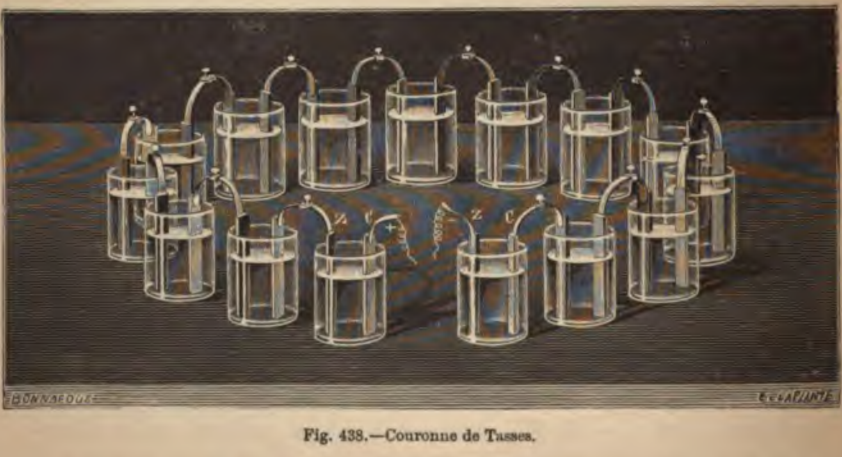

Fig. 438.—Couronne de Tasses.

513. Couronne de Tasses.—He shortly afterwards invented the *couronne de tasses* (crown of cups), consisting of a series of cups arranged in a circle, each containing salt water with a plate of silver or copper and a plate of zinc immersed in it, the silver or copper of each cup being connected with the zinc of the next, with the exception of the extreme plates. The last plate in liquid at each end of the series was connected with a plate of the other metal in air. These two plates in air are now known to be useless, and are omitted in the figure.

514. Trough Battery.—More convenient arrangements, equivalent to the couronne de tasses, were soon introduced. One of these, devised by Cruickshank, is represented in Fig. 439, consisting of a rectangular box, called a trough, of baked wood, which is a non-conductor of electricity, divided into compartments by partitions each consisting of a plate of zinc and a plate of copper soldered together. Dilute acid is poured into these compartments.

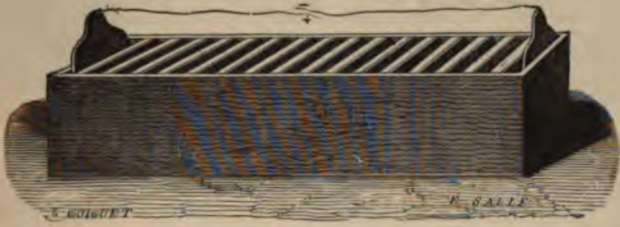

Fig. 439.—Cruickshank's Trough.

515. Wollaston's Battery.—In Wollaston's battery, the plates were suspended from a single horizontal bar, by means of which they could all be let down into the acid, or lifted out of it together. The liquid was contained either in compartments of a trough of glazed earthenware, with partitions of the same material, or in separate vessels as shown in Fig. 441. The plates were double-coppered; that is to say,

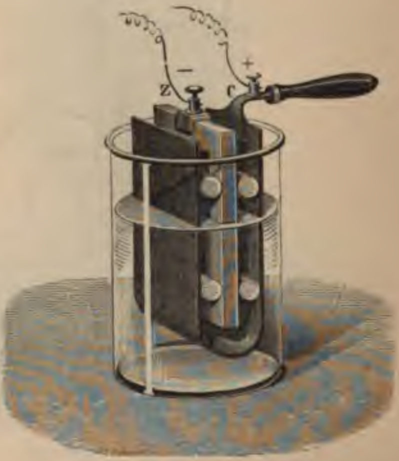

Fig. 440.—Wollaston's Cell.

they consisted of a zinc plate with a copper plate bent round it on both sides (Fig. 440), contact between them being prevented by pieces of wood or cork.

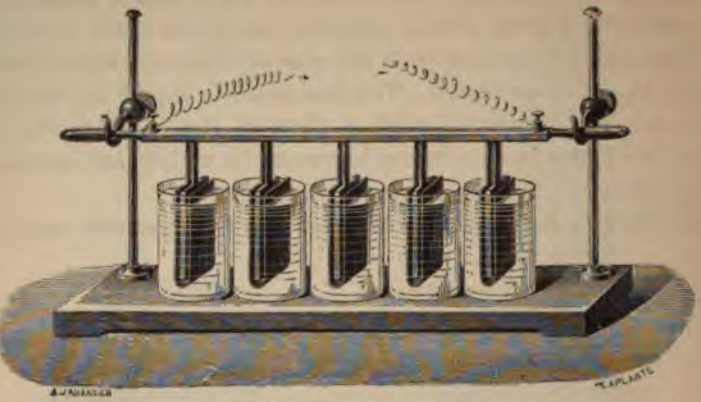

Fig. 441.—Wollaston's Battery.

517. Hare's Deflagrator.—For some purposes it is more important to diminish the resistance of a cell, or, in other words, to facilitate the conduction of electricity between the zinc and the copper plate, than to increase the electro-motive force by multiplying cells. The helical arrangement devised by Hare of Philadelphia (Fig. 443) is specially adapted to such purposes. It consists of two very large plates of zinc and copper rolled upon a central cylinder of wood, and prevented from touching each other by pieces of cloth or twine inserted between them. It is plunged in a tub of acidulated water, as represented in the figure. From the remarkably powerful heating effects which can be obtained by the use of this cell, it is called Hare's *deflagrator*.

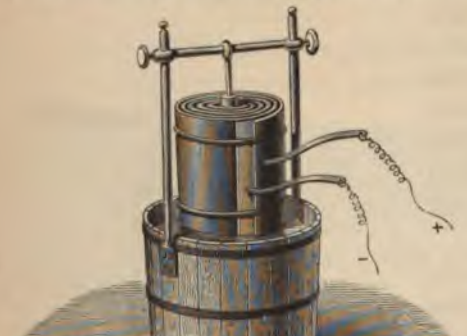

Fig. 443.—Hare's Deflagrator.

518. Polarization of Plates.—All the forms of battery which we have thus far described, are liable to a rapid decrease of power, owing to causes which are partly chemical and partly electrical.

The chemical action which takes place in each cell consists primarily in the formation of sulphate of zinc, at the expense of the zinc plate, the sulphuric acid, and the oxygen of the water with which the acid is diluted, the hydrogen of the water being thus liberated. As this action proceeds, the liquid becomes continually less capable of acting powerfully on the zinc. Again, a portion of the zinc which has been dissolved becomes deposited on the copper plate, thus tending to make the two plates alike, and so to destroy the current, which essentially depends on the difference between them.

But the most important cause of all is to be found in what is called the *polarization* of the copper plate; that is to say, in the deposition of a film of hydrogen on the surface of the plate. This film not only interposes resistance by its defect of conductivity, but also brings to bear an electro-motive force in the direction opposed to that of the current.

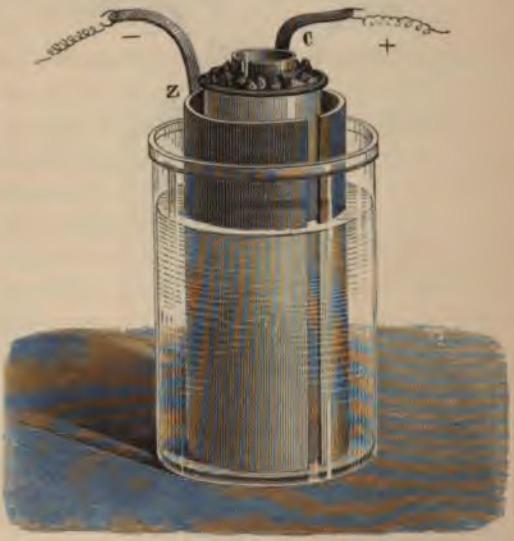

Fig. 444.—Daniell's Cell.

These obstacles to the maintenance of a constant current were first overcome by Daniell.

519. Daniell's Battery.—In the cell devised by Daniell, there is a porous partition of unglazed earthenware, separating the two liquids, which are in contact one with the zinc, and the other with the copper plate. These two liquids are not precisely alike, that which is in contact with the copper being not simply dilute sulphuric acid like the other, but containing also as much sulphate of copper as it will take up. For the purpose of keeping it saturated, crystals of sulphate of copper are suspended in it near its surface by means of a wire basket of copper. The effect of this arrangement is, that the hydrogen is intercepted before it can arrive at the copper plate, and the deposit which takes place on the copper plate is a deposit of copper, the hydrogen taking the place of this copper in the saturated solution.

The current given by a battery of these cells remains nearly constant for some hours.

In the figure, the copper plate C is represented as a cleft cylinder occupying the interior, with the crystals of sulphate of copper piled up round it. The entire cylinder surrounding these is the porous partition, outside of which is the cleft cylinder of zinc Z, the whole being contained in a vessel of glass.

It is more usual in this country to dispense with the glass vessel, and interchange the places of the zinc and copper in the figure, the copper plate being a cylindrical vessel of copper containing the saturated solution. In this is immersed the porous vessel containing the other fluid with the zinc plate immersed in it. The cells thus constructed are usually arranged in square compartments in a wooden box.

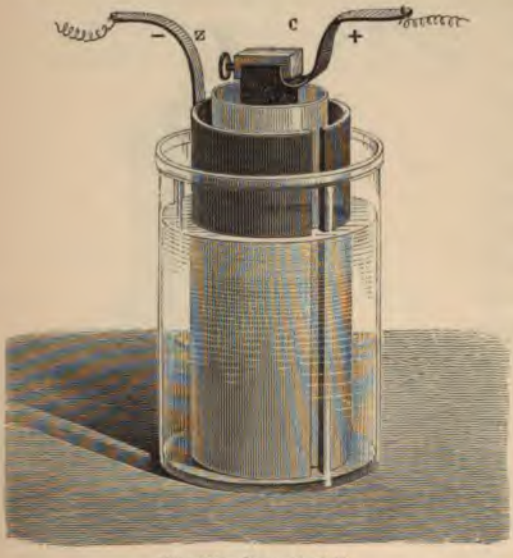

Fig. 445.—Bunsen's Cell.

520. Bunsen's Battery. — The battery which is now perhaps most extensively used for class experiments is that which was invented by Bunsen in 1843, being substantially identical with one previously invented by Grove, except that carbon is substituted for platinum.

The usual construction of its cells is very clearly represented in Fig. 445. The cleft cylinder is the zinc plate, which is immersed in dilute sulphuric acid. Within this is the porous cylinder, similar to Daniell's, containing *strong nitric acid,* in which is immersed a rectangular prism, of a very dense kind of charcoal, obtained from the interior of the retorts at gas-works, being deposited there in the manufacture of gas.

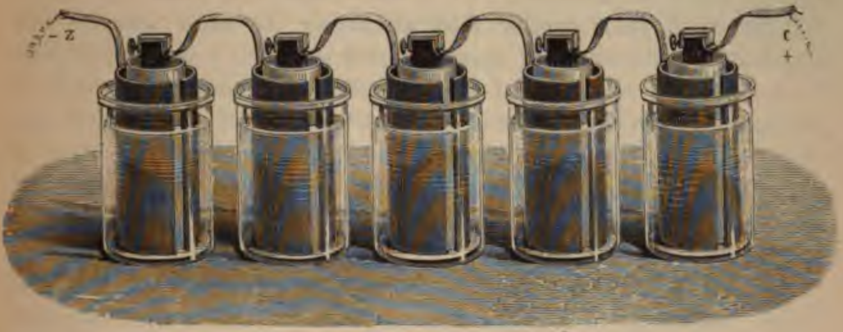

Fig. 446.—Bunsen's Battery.

In this cell the hydrogen is intercepted on its way to the carbon plate by the nitric acid, with which it forms nitrous acid.

Grove's battery possesses some advantages over Bunsen's; but its first cost is much greater.

521. Amalgamated Zinc.—When the poles of a battery are insulated from one another, there ought to be no chemical action in the cells. Any action which then goes on is wasteful, and is an indication that unproductive consumption of zinc goes on when the current is passing, in addition to the consumption which is necessary for producing the current. This wasteful action, which is called *local action*, goes on largely when the zinc plates are of ordinary commercial zinc, but not when they are of perfectly pure zinc. In this respect amalgamated zinc behaves like pure zinc, and it is accordingly almost universally employed. The amalgamation, which must be often renewed in the case of a battery in constant use, is performed by first cleaning the zinc plates with dilute acid, and then rubbing them with mercury.

522. Dry Pile: Bohnenberger's Electroscope.—For telegraphic purposes in this country, a battery is very commonly employed in which sand or sawdust, moistened with acidulated water, separates the zinc and copper plates of each cell.

The other forms of battery which have been devised are exceedingly numerous, and new forms are continually being introduced.

A *dry pile*, built up on the general plan of Volta's moist pile, was devised by De Luc, and improved by Zamboni. In Zamboni's construction, sheets of paper are prepared by pasting finely laminated zinc or tin on one side, and rubbing black oxide of manganese on the other. Discs are punched out of this paper, and piled up into a column, with their similar sides all facing the same way, to the number of a thousand or upwards, and are well pressed together. The difference of potential between the two ends is sufficient to produce sensible divergence of the gold-leaves of an electroscope, but the quantity of electricity which can be developed in a given time is exceedingly small. *No pile or battery can generate a sensible current, except by a sensible consumption of its materials in the shape of chemical action.*

A very delicate gold-leaf electroscope was devised by Bohnenberger, consisting of a single leaf suspended between the two poles of a dry pile, which for this purpose is arranged in two columns connected below, so that the poles are at the summits. If their lower ends, which form the middle of the series, be connected with the earth, one pole will always have positive, and the other negative potential. A very slight charge, positive or negative, given to the gold-leaf by means of the knob at the top of the case, suffices to make it move to the negative or the positive pole.

523. Thermo-electric Currents.—Electric currents can be produced by applying heat or cold to one of the junctions in a circuit composed of two different metals. This was first shown by Seebeck of Berlin in 1821. It may be illustrated by employing a rectangular frame (Fig. 448), having three sides formed of a copper plate, and the fourth of a cylinder of bismuth. It must be placed in the magnetic meridian, with a magnetized needle in its interior. On heating one of the junctions with a spirit-lamp, the needle will be deflected in such a direction as to indicate the existence of a current, which, in the copper portion of the circuit, flows from the hot to the cold junction, and in the bismuth portion from the cold to the hot. If cold instead of heat be applied to one junction, the direction of the current will still be from the warmer junction

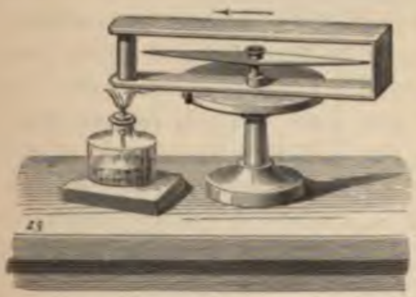

Fig. 448.—Thermo-electric Current.

through the copper to the colder junction, and from this through the bismuth to the warmer junction. Antimony, if employed instead of copper, gives a still more powerful effect.

524. Though a circuit composed of bismuth and antimony is specially susceptible of thermo-electric excitation, the property is possessed, in a more or less marked degree, by every circuit composed of two metals, and even by circuits composed of the same metal in different states. If, for example, a knot or a helix (as in Fig. 449), be formed in a piece of platinum wire, and heat applied at one side of it, a current will be indicated by a delicate galvanometer. In metals which are usually heterogeneous in their structure, such as bismuth, it is not uncommon to find currents produced by heating parts which appear quite uniform. If the ends of two copper wires be bent into hooks, and one of them be heated, on placing them in contact, a current will be produced due to the presence of a thin film of oxide on the heated wire. With two platinum wires, no such effect is obtained.

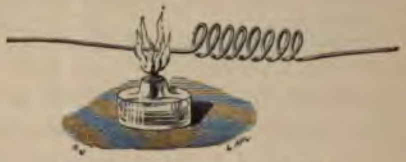
Fig. 449.—Current with one Metal.

525. Thermo-electric Order.—According to Becquerel's experiments, the metals may be ranged in the following order, as regards the direction of the current produced by heating a junction of any two of them:—*Bismuth, platinum, lead, tin, copper, silver, zinc, iron, antimony;* that is to say, if a junction of any two of these metals be heated, the direction of the current at the junction in question will be from that which stands first in the list to the other. His experiments have also established the important fact that the current obtained by heating all the junctions B, C, D, E, F, of a chain of dissimilar metals to one common temperature, is the same as that obtained by uniting the two extreme bars AB, FG, directly to each other, and heating their junction to the same temperature.[1]

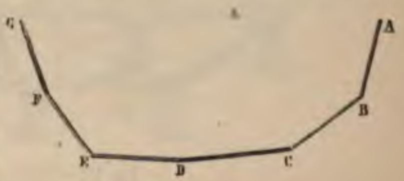

Fig. 451.

526. Comparison of Electro-motive Forces.—By employing a chain composed of wires of different metals soldered together, with its two extremities connected with a galvanometer, and heating one junction to 20° C., while the rest were kept at 0° C., Becquerel obtained currents proportional to the following numbers:—

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[1] The more accurate statement is, that the *electro-motive force* is the same in the two cases. The *current* will be sensibly the same if the resistance in BCDEF is insignificant in comparison with the rest of the circuit. In order that there may be a current, the

Junction heated.	Current.	Junction heated.	Current.
Iron – silver,	26·20	Copper – platinum,	8·55
Iron – copper,	27·96	Copper – tin,	3·50
Iron – tin,	31·24	Silver – copper,	2·00
Iron – platinum,	36·07	Zinc – copper,	1·00

On comparing these numbers, it will be found that they are in approximate agreement with the law above stated. Thus the electromotive force of a silver-platinum circuit comes out 10·55 by adding 2·00 to 8·55, and 9·87 by subtracting 26·20 from 36·07. The electromotive force of copper-platinum is 8·55 as observed directly, and 8·11 as computed by taking the difference of iron-copper and iron-platinum. The deviation from precise agreement is not more than may fairly be ascribed to errors of observation.

527. Influence of Temperature.—When the junctions in a thermo-electric circuit are at only two temperatures, the lower of which remains constant while the other varies, the current will be sensibly proportional to the difference of temperature only as long as this difference is small. As the difference goes on increasing, the current increases less rapidly, then decreases, and at still greater differences of temperature is reversed.

528. Thermo-electric Pile.—If a thermo-electric chain be composed of two metals occurring alternately (as in Fig. 452), no effect will be obtained by equally heating *two consecutive* junctions; for the current which would be generated by heating the one is in the opposite direction to that due to the heating of the other. If we number the

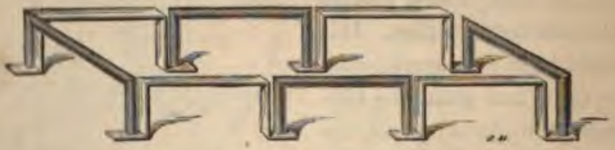

Fig. 452.—Pouillet's Thermo-pile.

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circuit must of course be completed, and not left open as in Fig. 451. In the case of an open circuit, the result of the heating will simply be to produce difference of potential between the extremities A, G. This difference of potential is the measure of the electromotive force, and will accordingly be the same in the two cases.

junctions in order, we shall obtain a current in one direction by heating any junction which bears an odd number, and in the opposite direction by heating any one that bears an even number. The thermo-electric pile, or *thermo-pile,* whose use has been already described in connection with experiments on radiant heat (§ 313), is an arrangement of this kind, in which all the odd junctions are presented together at one end, and all the even junctions at the other, the two metals composing the pile being antimony and bismuth. The electromotive force obtained with a given difference of temperature between the ends of the pile is proportional to the number of junctions, except in so far as accidental differences may exist between different junctions.

529. Application to Measurement of Temperature.—Thermo-electric currents may be employed either in testing equality of temperatures, or in comparing small differences of temperature. As an example of the former application, suppose a circuit to be formed of two long wires, one of iron and the other of copper, connected at both ends, and covered with gutta-percha or some other insulator except at the two junctions. Let one junction be lowered to the bottom of a boring, or any other inaccessible place whose temperature we wish to ascertain, and let the other junction be immersed in a vessel of water containing a thermometer. If one of the wires be carried round a galvanometer, the direction in which the needle is deflected will indicate whether the upper or lower junction is the warmer, and if we alter the temperature of the water in the vessel till the deflection is reduced to zero, we know that the two junctions are at the same temperature, which we can read off by the thermometer immersed in the water.

CHAPTER XLVI.

GALVANOMETER.

530. Œrsted's Experiment.—The discovery by the Danish philosopher Œrsted, in 1819, that a magnetized needle could be deflected by an electric current, was justly regarded with intense interest by the scientific world, as affording the first indication of a definite relation existing between magnetism and electricity.

Œrsted's experiment can be repeated by means of the apparatus represented in Fig. 456. Two insulated metallic wires are placed in the magnetic meridian, one of them above, and the other below a magnetized needle. If a current be sent through one of these wires, the needle will be deflected; and if the current be strong, the deflection will nearly amount to a right angle. The direction of the deflection will be reversed if the current be passed through the lower instead of the upper wire. It will also be reversed by reversing the direction of the current. In the figure, the current is supposed to be passing above the needle from south to north. In this case the north end of the needle moves to the west, and the south end to the east. On making the current pass in various directions, either horizontally, vertically, or obliquely, near one pole of the needle, it will be found that deviation is always produced except when the plane containing the pole and current is perpendicular to the length of the needle.

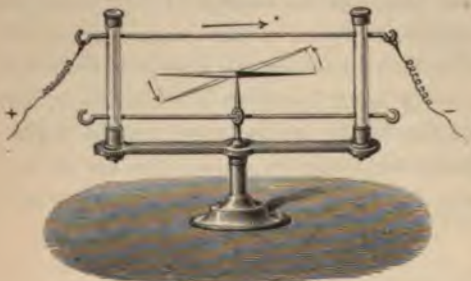

Fig. 456.—Œrsted's Experiment.

531. Ampère's Rule.—The direction in which either pole of a needle is deflected by a current, whatever their relative positions may be, is given by the following rule, which was first laid down by Ampère.

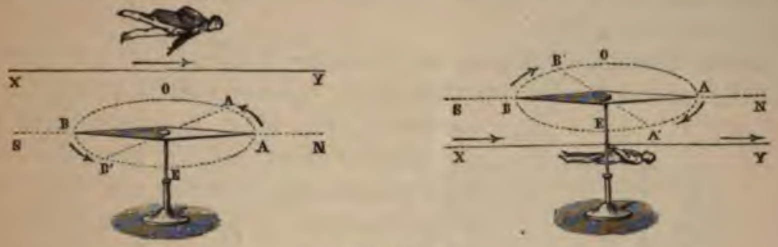

Fig 457. Ampère's Law. Fig. 458.

Imagine an observer to be so placed that the current passes through him, *entering at his feet* and leaving at his head, then the deflection of a *north-seeking pole* will be *to the left* as seen by him. The deflection of a south-seeking pole will be in the opposite direction. The two figures 457, 458 illustrate the application of this rule to the two cases just considered. The current is supposed, in both cases, to be flowing from south to north. A is the austral or north-seeking pole of the needle, and B the boreal or south-seeking pole.

531 A. Lines of Magnetic Force due to Current.—The relation between currents and magnetic forces may be more precisely expressed by saying that a current flowing through a straight wire produces circular lines of force, having the wire for their common axis. A pole of a magnet placed anywhere in the neighbourhood of the wire, experiences a force tending to urge it in a circular path round the wire, and the direction of motion round the wire is opposite for opposite poles. Fig. 458 A represents three of the lines of force for a north-seeking pole, due to a current flowing through a straight wire from the end marked + to the end marked —. The lines of force are circles (shown in perspective as ellipses), having their centre at a point C in the wire, and having their plane perpendicular to the length of the wire. The arrows indicate the direction in which a north-

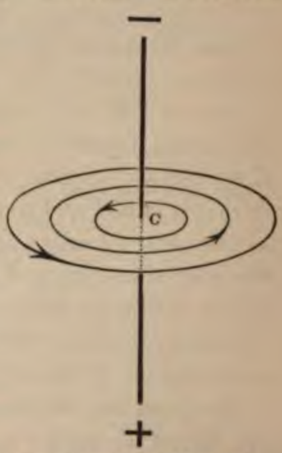

Fig. 458 A.—Lines of Force due to Current.

seeking pole will be urged. This direction is from right to left round the wire as seen from the wire itself by a person with his feet towards + and his head towards −, according to Ampère's rule. The figure may be turned upside down, or into any other position, and will still remain true.

531 B. Reaction of Magnet on Current.—While the wire, in virtue of the current flowing up through it, urges an austral pole from A towards A′ (Fig. 458 B), it is itself urged in the opposite direction C C′. If an observer be in imagination identified with the wire, the current being supposed, as in Ampère's rule, to enter at his feet, and come out at his head, the force which he will experience from a north-seeking pole directly in front of him will be a force to his right. It will be noted that the magnetic influence which thus urges him to the right, would urge a north-seeking pole from his front to his back. *A conductor conveying a current is not urged along lines of magnetic force, but in a direction which is at right angles to them, and at the same time at right angles to its own length.*

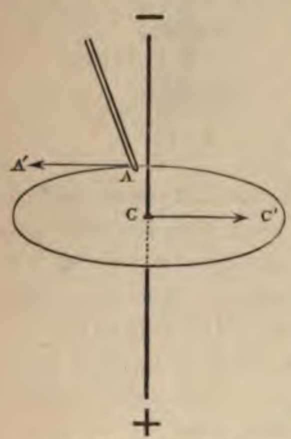

Fig. 458 B.—Reaction on Current.

532. Numerical Estimate of Currents.—The numerical measure of a current denotes the quantity of electricity which flows across a section of it in unit time. It is sometimes called *strength* of current, sometimes, especially by French writers, *intensity* of current, sometimes simply *current* or *amount* of current. If a thin and a thick wire are joined end to end, it has the same value for them both; just as the same quantity of water flows through the broad as through the contracted parts of the bed of a stream. Hence the name *intensity* is obviously inappropriate, for, with the same total quantity of electricity flowing through both, the current is, properly speaking, more *intense* in the thin than in the thick wire.

Currents may be measured experimentally by various tests, which are found to agree precisely. The most convenient of these for general purposes is the deflection of a magnetized needle. The force which a given pole experiences in a given position with respect to a wire conveying a current, is simply proportional to the current. Hence the name *strength* of current admits of being interpreted in a sense corresponding to that in which we speak of the strength of a pole. Instruments for measuring currents by means of the deflections which they produce in a magnetized needle are called *galvanometers.*

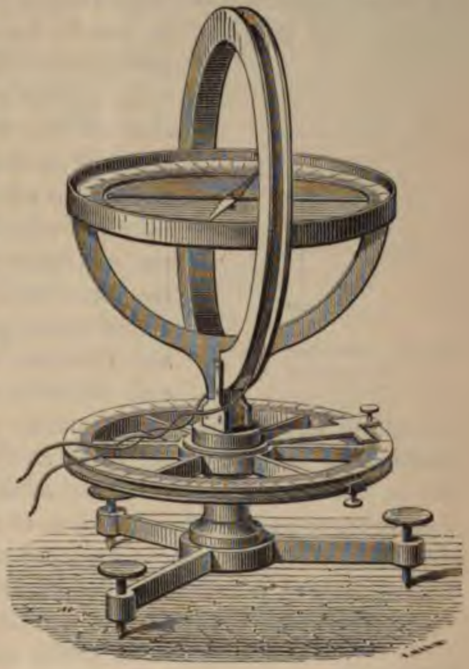

Fig. 459.—Sine Galvanometer.

533. Sine Galvanometer.—The sine galvanometer, which was invented by Pouillet, is represented in Fig. 459. The current which is to be measured traverses a copper wire, wrapped round with silk for insulation, which is carried either once or several times round a vertical circle; and this circle can be turned into any position in azimuth, the amount of turning being indicated on a horizontal circle. In the centre of the vertical circle, a declination needle is mounted, surrounded by a horizontal circle for indicating its position, this circle being rigidly attached to the vertical circle. Suppose that, before the current is allowed to pass, both the needle and the vertical circle are in the magnetic meridian, and that the needle consequently points at zero on its horizontal circle. On the current passing, the needle will move away. The vertical circle must then be turned until it overtakes the needle; that is, until the needle again points at zero. This implies turning the circles through an angle α equal to that by which the needle finally deviates from the magnetic meridian. In this position the terrestrial couple tending to bring back the needle to the meridian is proportional to $\sin \alpha$ (§ 498). The forces exerted upon the two poles by the current are perpendicular to the plane of the vertical circle, and are simply proportional to the current. Hence, in comparing different observations made with the same instrument, the amounts of current are proportional to the sines of the deviations.

534. Tangent Galvanometer.—The tangent galvanometer, which is simpler in its construction and use, and is much more frequently employed, consists of a declination needle mounted in the centre of a vertical circle whose plane always coincides with the magnetic meridian, the length of the needle being small in comparison with the radius of the circle.

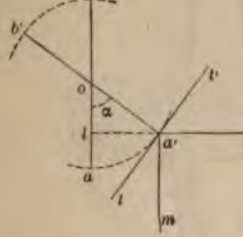

Fig. 460.—Principle of Tangent Galvanometer

Let o (Fig. 460) be the centre of suspension, $a\,b$ the initial position of the needle, and $a'\,b'$ its deflected position. The force F exerted on either pole by the current is sensibly the same at a' as at a on account of the smallness of the needle, and it acts in the direction lk, while the horizontal force of the earth upon the pole acts along $a'm$; and these two forces give a resultant along oa'. Hence, taking the triangle ola' as the triangle of forces,[1] the force exerted by the current is to the horizontal force exerted by the earth as la' to ol, or as $\tan \alpha$ to unity; that is, the current is proportional to the tangent of the deflection.

In order to permit the deviations of the short needle to be accurately read, a long pointer is attached to it, usually at right angles, the two ends of which move along a fixed horizontal circle.

535. Multiplier.—The idea of carrying a wire several times round a needle in a vertical plane is due to Schweiger. The form of apparatus designed by him, called *Schweiger's multiplier*, is represented in Fig. 461. The difference between the rectangular and the circular form is merely a matter of detail. The name *multiplier* is derived from the fact that, if the current is not sensibly diminished by increasing the number of convolutions of wire through which it has to pass, the force exerted on the needle is n times as great with n convolutions as with only 1, since each convolution exerts its own force on the needle independent of the rest. Cases, however, frequently occur in which the increased *resistance* introduced by increasing the number of convolu-

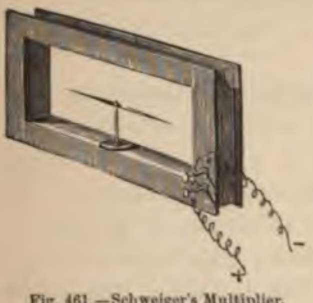

Fig. 461.—Schweiger's Multiplier.

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[1] The parallelogram of forces is divided by its diagonal into two triangles, either of which may be called the triangle of forces.

tions outweighs the advantage of multiplication, so that a short thick wire with few convolutions gives a more powerful effect than a long thin wire with many. This is especially the case with thermo-electric currents. The names *multiplier* and *galvanometer* are commonly used as equivalent.

The difference between the rectangular and the circular form is merely a matter of detail. Whichever form be adopted, all parts of the coil contribute to make the needle deviate in the same direction. For instance, in Fig. 462, if the current proceeds in the direction indicated by the arrows, the application of Ampère's rule to any one of the four sides of the rectangle shows that the austral pole *a* will be urged towards the front of the figure. When the coil is circular, and the needle so small that each pole is nearly in the centre, equal lengths of the current, in whatever parts of the circle they may be situated, exert equal forces upon the needle, and all alike urge the poles in directions perpendicular to the plane of the coil.

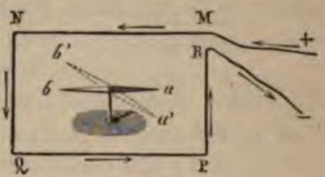

Fig. 462.

535 A. Differential Galvanometer.—The coil of a galvanometer sometimes consists of two distinct wires, having the same number of convolutions, and connected with separate binding-screws. This arrangement allows of currents from two distinct sources being sent at the same time round the coil either in the same or in opposite directions. In the latter case, the resultant effect upon the needle will be that due to the difference of the two currents; and if they are not exactly equal, the direction of the deflection will indicate which of them is the greater. An instrument thus arranged is called a *differential galvanometer.*

536. Astatic Needle.—The sensibility of the galvanometer is greatly increased by employing what is called an *astatic* needle. It consists of a combination of two magnetized needles *with their poles turned opposite ways.* The two needles are rigidly attached at different heights to a vertical stem, and the system is usually suspended by a silk fibre, which gives greater freedom of motion than support upon a point. On account of the opposition of the poles, the directive action of the earth on the system is very feeble. If the magnetic moments of the two needles were exactly equal, the resultant moment would be zero, and the system would remain indifferently in all azimuths.

One of the needles ab (Fig. 463) is nearly in the centre of the coil CDEF through which the current passes. The other $a'b'$ is just above the coil. When a current traverses the coil in the direction of the arrows, the action of all parts of the current upon the lower needle tends to urge the austral pole a towards the back of the figure, and the boreal pole b to the front. The upper needle $a'b'$ is affected principally by the current in the upper part CD of the coil, which urges the austral pole a' to the front of the figure and the boreal pole b' to the back. Both needles are thus urged to rotate in the same direction by the current, and as the opposing action of the earth is greatly enfeebled by the combination, a much larger deflection is obtained than would be given by one of the needles if employed alone.

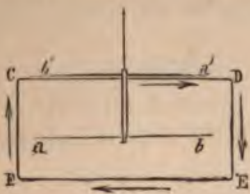

Fig. 463.

If the two needles had rigorously equal moments, the system would be said to be *perfectly astatic*. The smallest current in the coil would then suffice to set the needles at right angles to the meridian, and no measure would be obtained of the amount of current.

Fig. 464 represents an astatic galvanometer, as usually constructed. The coil is wound upon an ivory frame, which supports the divided circle in whose centre the upper needle is suspended. The ends of the coil are connected with two binding-screws for making connection with the wires which convey the current to be measured. The needles are usually two sewing-needles, and the upper one often carries a light pointer. The suspending fibre is attached at its upper end to a hook, which can be raised or lowered,

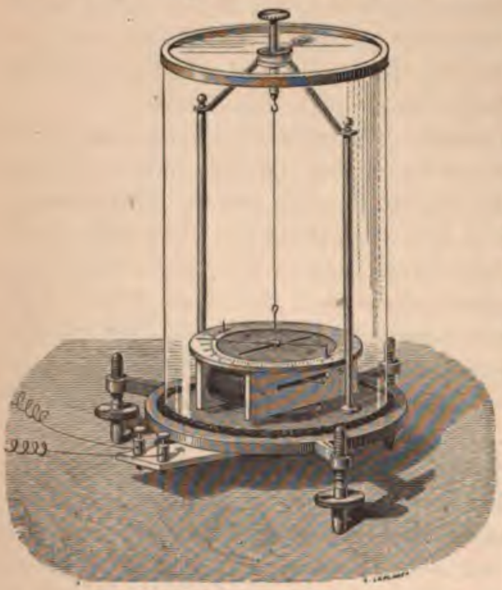

Fig. 464.—Astatic Galvanometer.

and when the instrument is not in use this is lowered till the upper needle rests upon the plate beneath it, so as to relieve the fibre from strain. In using the instrument, care must be taken to adjust the three levelling-screws so that the needle swings free.

536 A. Thomson's Mirror Galvanometer.—The most sensitive galvanometer as yet invented is the mirror galvanometer of Sir W. Thomson. Its needle, which is very short, is rigidly attached to a small light concave mirror, and suspended in the centre of a vertical coil of very small diameter by a silk fibre. A movable magnet is provided for bringing the needle into the plane of the coil when the latter does not coincide with the magnetic meridian. A divided scale is placed in a horizontal position in front of the mirror, at the distance of about a yard, and the image of an illuminated slit, which is thrown by the mirror upon this scale, serves as the index. The arrangement of the mirror and scale, which is the same as in the case of the quadrant electrometer described in a previous chapter, is exhibited in Fig. 464 A. M is the mirror of silvered glass, slightly concave, with a small piece of magnetized watch-spring attached to its back, the two together weighing only a grain and a half, and suspended by a few fibres of unspun silk. A A is a divided scale forming an arc of a horizontal circle about the mirror as centre. Immediately below the centre of this scale is a circular opening S with a fine wire stretched vertically at the back of it. A paraffine lamp L is placed directly behind this opening, so as to shine through it upon the mirror, which is at such a distance as to throw upon the screen a bright image of the opening with a sharply-defined dark image of the wire in its centre. The image of the wire is employed as the index in taking the readings.

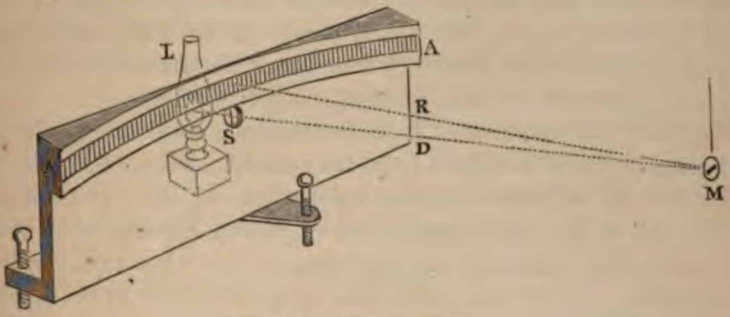

Fig. 464 A.—Mirror and Scale.

For use at sea, the galvanometer is modified by fastening the supporting fibre of silk at both ends, so as to keep it tight, with the needle and mirror attached at its centre, care being taken to make the direction of the fibre pass through the common centre of gravity of the needle and mirror, in order that the rolling of the ship may not tend to produce rotation. In this form it is called the *marine galvanometer*.

537. Calibration of Galvanometer.—The deviations of the needle of a galvanometer are not in general proportional to the currents which produce them. In order to be able to translate the indications of the instrument into proportional measure, a preliminary investigation must be made, and its results embodied in a table. This has been done in several ways. We shall merely indicate the method employed by Melloni for deducing from the deflections of his galvanometer the amounts of heat received by his thermo-pile.

He placed two sources of heat opposite the two ends of the pile, and allowed them to radiate to it, first one at a time, and then both together. One of them produced a deviation, say of 5°, and the other of 10°, and when the two were acting jointly the deviation was 5°. Since the latter number is the difference of the other two, the inference is that up to 10° the deflections are proportional to the amounts of heat received. Melloni thus established that the proportionality subsisted up to 20°. When the two sources separately produced deflections of 20° and 25°, and a deflection of 6°·5 jointly, he inferred that a deflection of 25° indicated an amount of heat represented by 26°·5; for the heat which produced the deflection of 25° was the sum of the two amounts represented separately by 20° and 6°·5. By a succession of steps of this kind, the calibration[1] (as this process is called) can be extended nearly to 90°.

This mode of investigation covers any want of proportionality which may exist in the production of thermo-electric currents, as well as in the proportionality of these currents to the deflections. Another method of calibrating a galvanometer will be described in the next chapter.

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[1] The application of the name calibration to this process is, we believe, due to Professor Tyndall. Its analogy to the calibration of a thermometer is obvious; the object in both cases being to reduce observed differences to proportional measure. It is often called the graduation of a galvanometer; but, in point of fact, the galvanometer is graduated, by dividing its circle into 360 degrees, before the process begins.

CHAPTER XLVII.

OHM'S LAW.

538. Statement of Ohm's Law.—The strength of the current which traverses a circuit depends partly on the electro-motive force of the source of electricity, and partly on the resistance of the circuit. For equal resistances, it is proportional to the whole electro-motive force tending to maintain the current, and for equal electro-motive forces it is inversely as the whole resistance in the circuit. Hence, when proper units are chosen for expressing the current C, the resistance R, and the electro-motive force E, we have

$$C = \frac{E}{R},$$

or *the current is equal to the electro-motive force divided by the resistance.* This is Ohm's law, so called from its discoverer.

539. Explanation of the term Electro-motive Force.—Whenever an acid is in contact with a metal liable to be acted upon by it, a difference of potential exists at the surface of contact, the acid having higher potential than the metal. In a galvanic circuit, the tendency of this difference of potential is to force a current round from the acid through the rest of the circuit to the metal. In a battery consisting of several cells arranged in a series, the total electro-motive force is the sum of the forces of the separate cells; and if the circuit be interrupted at any one place, and the potentials at the two sides of the interruption be examined by Thomson's quadrant electrometer, they will exhibit a difference which is the sum of the differences exhibited by the separate cells when similarly examined. A similar difference, but usually much smaller, is exhibited by the two poles of a thermo-electric pile when its two faces are at different temperatures, and is the sum of the differences due to the separate elements.

When the current is passing round a galvanic circuit there is, in each cell, a gradual fall of potential from the film of liquid in contact with the zinc to the film in contact with the carbon or copper plate, and there is also a gradual fall in the connecting wire from the last carbon (or the positive pole) to the first zinc (or the negative pole), the sum of all these gradual falls being precisely equal to the sum of all the sudden rises[1] which occur at the surfaces of contact between metal and liquid. The sum of all these sudden rises constitutes the whole electro-motive force of the circuit.

In like manner, in a thermo-electric circuit, there is difference of potential probably at each junction, whatever its temperature may be; and the algebraic sum of these sudden differences (a rise of potential being called positive and a fall negative, in travelling with the current) is the whole electro-motive force of the thermo-pile. When the faces of the pile are at equal temperatures, the opposite electro-motive forces are equal, and destroy one another; when the temperatures are unequal, the positive electro-motive forces exceed the negative, and the total or resultant electro-motive force is the measure of this excess.

540. Explanation of the term Resistance.—When the current of a circuit is taken through the coil of a galvanometer, it is found that, by introducing different lengths of connecting wire, very different amounts of deflection can be obtained. The longer the wire which connects either pole of the battery with the galvanometer, the smaller is the deflection; and a small deflection indicates a feeble current. The current is in like manner weakened by introducing a fine instead of a stout wire, if their length and material be the same, or by introducing an iron wire instead of a copper wire of the same dimensions. These differences in the properties of the different wires are expressed by saying that they have different resistances.

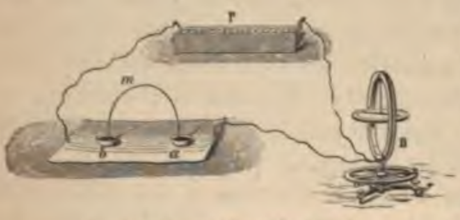

Fig. 465.—Comparison of Resistances.

The apparatus represented in Fig. 465 can be employed for comparing resistances in this way. The current given by a battery P passes through a wire to the galvanometer B, and after traversing its coil is led on by another wire to the cup of mercury *a*, thence through the connecting wire *m* to the other cup of mercury *b*, and back to the battery through another wire. The circuit can also be completed as shown in the figure, without passing through *m*, by means of a broad conducting plate whose resistance may be neglected.

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[1] If any sudden falls occur, it is the algebraic sum (that is the excess of sudden rises above sudden falls) that is to be here understood.

In changing the wire *m*, it is found that, to produce no change in the deflection, the length of the wire must vary directly as its cross-section; that is to say, if l, l', l'' . . . . be the lengths of different wires employed, and $s\ s'\ s''$ . . . . their sectional areas, their resistances will be equal, if

$$\frac{l}{s}=\frac{l'}{s'}=\frac{l''}{s''} \ldots\ldots$$

This is on the supposition that the wires are all of precisely the same material. Every substance has its own specific resistance, the reciprocal of which is its electrical conductivity and is precisely analogous to thermal conductivity. Denoting specific resistances by $r, r', r'', \ldots.$ the condition of equal resistances, when the materials are different, is

$$\frac{rl}{s}=\frac{r'l'}{s'}=\frac{r''l''}{s''} \ldots\ldots$$

and the resistance of any wire is expressed by the formula $\frac{rl}{s}$, l denoting its length, s its sectional area, and r the specific resistance of its material.

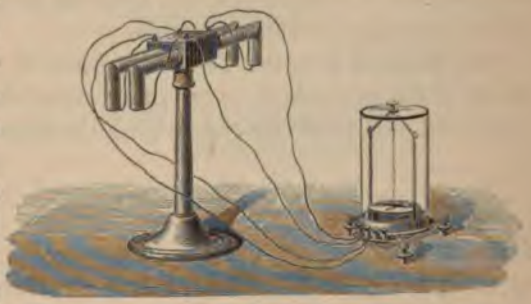

Fig. 466.—Pouillet's Comparison.

541. Experimental Proofs of Ohm's Law.—Pouillet, who conducted numerous experiments bearing on Ohm's law, investigated the connection between currents and resistances in the following ways:—

1. *For thermo-electric currents,* he employed two thermo-electric elements, each consisting of a stout cylinder of bismuth with its ends bent down and soldered to copper wires. The two elements were arranged side by side as in Fig. 466, and the junctions at one end were immersed in hot water, those at the other end being kept in melting ice. The hot and cold junctions of the one were connected

by a wire which was carried round a galvanometer needle. Those of the other were connected by a wire ten times as long, which made ten times as many turns round the same needle in the opposite direction, so that the two currents opposed each other in their action on the needle. It was found that the needle remained at zero, showing that the current in the short wire was ten times as strong as the other, for one of its convolutions was able to balance ten convolutions of the other. As the resistance in the stout bars of bismuth was inappreciable, it followed that the currents in the two circuits were inversely as the resistances.

2. *For voltaic currents*, he first sent the current of a battery through a galvanometer without any interposed resistance, and observed the strength of current C. He then introduced, successively, known lengths of uniform wire l_1, l_2, l_3, and observed the currents obtained. Denoting these by C_1, C_2, C_3, and taking x to denote the length of wire which would be equivalent to the unknown resistance of the original circuit consisting only of the battery and the galvanometer, we should have—

$$\frac{c}{c_1} = \frac{x+l_1}{x}\ ,\quad \frac{c}{c_2} = \frac{x+l_2}{x}\ ,\quad \frac{c}{c_3} = \frac{x+l_3}{x}.$$

From any one of these three equations x can be determined, and Ohm's law is verified if they all give the same value of x. This Pouillet found to be the case.

By repeating the experiment with a different kind of wire, a new value of x will be obtained, and thus the resistances of equal lengths of the two wires can be compared.

542. Reduced Length: Total Resistance of Circuit.—To express, in terms of the equivalent length of one wire, the resistance of a circuit composed of several, we can employ the relation (§ 540)

$$\frac{rl}{s} = \frac{r'l'}{s'}\text{; whence } l = \frac{s}{s'}\,\frac{r'}{r}\,l',$$

l denoting the length of one kind of wire equivalent to the length l' of the other. The length l is called the reduced length of the wire whose actual length is l'.

543. Rheostat.—Wheatstone's *rheostat* is a very convenient instrument for the comparison of resistances. It consists (Fig. 467) of two cylinders, one of brass, and the other of non-conducting material, so arranged that a copper wire can be wound off the one on to the other by turning a handle. The surface of the non-conducting cylinder B has a screw-thread cut in it, for its whole length, in which the wire lies, so that its successive convolutions are well insulated from each other. Two binding-screws are provided for introducing the rheostat into a circuit; and the resistance which is thus introduced depends on the length of wire which is wrapped upon the non-conducting cylinder, for the brass cylinder A has so large a section that its resistance may be neglected. The amount of resistance can thus be varied as gradually as we please by winding on and off. The handle can be shifted from one cylinder to the other. The figure shows it in the position for winding wire off A on to B. The number of convolutions of wire on B can be read off on a graduated bar provided for the purpose, and parts of a revolution are indicated on a circle at one end.

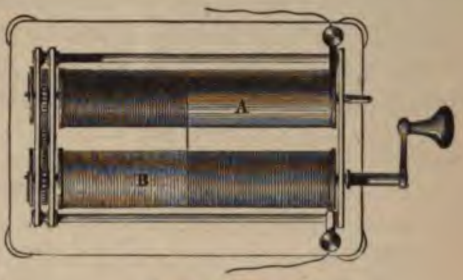

Fig. 467.—Rheostat.

Fig. 468 represents a very direct mode of measuring resistances by the rheostat. The current traverses a galvanometer B, a rheostat R, and the conductor *m*, whose resistance is to be measured, the whole of the wire of the rheostat being wound on the brass cylinder. The deflection of the galvanometer having been observed, the conductor *m* is taken out of circuit, the two wires at *a* and *b* are directly connected, and as much of the rheostat wire is brought into circuit as suffices to reduce the deflection to its former amount.

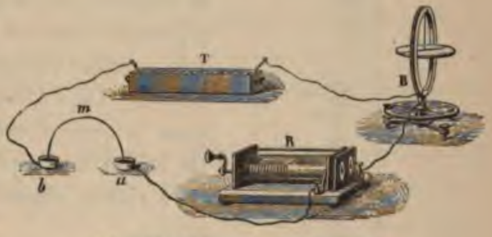

Fig. 468.—Measurement of Resistance.

543 A. Specific Resistances and Conductivities.—Numerous experimenters have compared the specific resistances of the different metals. Though the results thus obtained exhibit some diversity, they all agree in making silver, gold, and copper the three best conductors. Slight impurities, especially in the case of copper, have a very great effect in diminishing conductivity, or, in other words, in increasing resistance. Resistance is also increased, in the case of metals, by increase of temperature.

Forbes has pointed out that the order of the metals as regards their conductivity for heat is the same as for electricity. The effects of impurity and of change of temperature are also alike in the two cases, as has been recently shown by Professor Tait.

The following are E. Becquerel's determinations of specific electrical resistance at the temperature 15° C., the resistance of silver at 0° C. being denoted by 100:—

SPECIFIC RESISTANCES AT 15° C.

Silver,	107	Palladium,	715
Copper,	112	Iron,	825
Gold,	155	Lead,	1213
Cadmium,	407	Platinum,	1243
Zinc,	414	Mercury,	5550
Tin,	734		

On comparing this list with the list of thermal conductivities, § 333, it will be observed that the order is precisely the same as far as the comparison extends, and that the numerical values are nearly in inverse proportion, showing that electrical and thermal *conductivities* are nearly in direct proportion.

544. Resistance of Liquids.—The resistance of liquids can be determined on similar principles, the current being transmitted between two parallel plates of metal immersed in the liquid. One form of apparatus for this purpose is represented in Fig. 469. Care must be taken to employ metals which will not give rise to electro-motive force by chemical action.

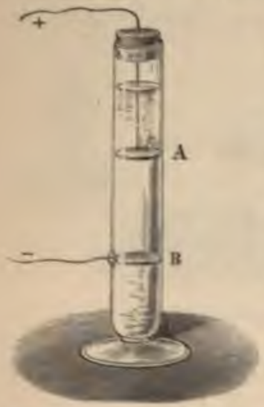

Fig. 469.—Resistance of Liquids.

The resistance even of the best conducting liquids, except mercury, is enormously greater than that of metals. For instance, in round numbers, the resistance of dilute sulphuric acid is a million times, and that of solution of sulphate of copper ten million times greater than that of pure silver. The resistance of pure water is very much greater than either of these.

In the cells of a galvanic battery, the current has to traverse liquid conductors, and the resistance of these is sometimes a large part of the whole resistance in circuit. It is diminished by bringing the plates nearer together, and by increasing their size, since the former change involves diminution of length, and the latter increase of sectional area in the liquid conductor to be traversed. This is the only advantage of large plates over small ones, the electro-motive force being the same for both. The advantage of the double coppers in Wollaston's battery (§ 515) is similarly explained, the resistance with this arrangement being about half what it would be with copper on only one side of the zinc, at the same distance.

545. Calibration of Galvanometer by the Rheostat.—The rheostat can be employed for determining the relative values of the deflections of a galvanometer. For this purpose the two instruments are to be introduced into the circuit of a battery, and in the first instance all the wire of the rheostat is to be on the non-conducting cylinder. The deflection, which will then be comparatively small, is to be noted. Successive lengths of the rheostat wire are then to be wound off, so as to diminish the resistance, and the deflections are to be noted in each case. If the current, when the whole length l of rheostat wire was in circuit, be denoted by C, and the currents with lengths $l_1\, l_2$. in circuit by $C_1\, C_2$ . . . . , and if r denote the resistance of the battery and galvanometer, which can be determined by methods already explained, we shall have

$$\frac{C_1}{C}=\frac{r+l}{r+l_1}\;,\quad \frac{C_2}{C}=\frac{r+l}{r+l_2}\;\ldots\ldots$$

Hence the ratios of the currents C, C_1, C_2 . . . corresponding to the observed deflections are known.

546. Arrangement of Cells in Battery.—Suppose that we have a number n of precisely similar cells, each having electro-motive force e and resistance r, and that we connect them in a series, as in Figs. 434, 446, with a conductor of resistance R joining their poles. The whole electro-motive force in the circuit will then be ne, and the whole resistance will be $nr+R$; hence the strength of current will be

$$C=\frac{ne}{nr+R}.$$

This formula shows that, if the external resistance R is much greater than the resistance in the battery nr, any change in the number of cells will produce a nearly proportional change in the current; but that when the external resistance is much less than that of one cell, as is the case when the poles are connected by a short thick wire, a change in the number of cells affects numerator and denominator almost alike, and produces no sensible change in the current. It is impossible, by connecting any number of similar cells *in a series*, to obtain a current exceeding $\frac{e}{r}$, which is precisely the current which one of the cells would give alone if its plates were well connected by a short thick wire.

It is possible, however, by a different arrangement of the cells, to obtain a current about n times stronger than this, namely, by connecting all the zinc plates to one end of a conductor, and all the carbons or coppers to the other end, as in Fig. 470. In the arrangement of three cells here figured, the current which passes through the spiral connecting wire is the sum of the currents which the three cells would give separately. The arrangement is equivalent to a single cell with plates three times as large superficially, and at the same distance apart. The electro-motive force with n cells so arranged is simply e, but the resistance is only $\frac{r}{n} + R$, so that the current is

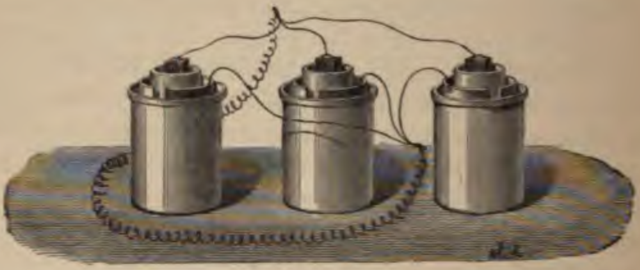
Fig. 470.—Cells with similar Plates connected.

$$C = \frac{e}{\frac{r}{n} + R} = \frac{ne}{r + nR}.$$

This system of arrangement may be called *arranging the cells as one element*. It has sometimes been called the *arrangement for quantity*, the arrangement in a series being called the *arrangement for intensity*.

If in Fig. 470 we substitute for each of the three cells a *series* consisting of four cells, the electro-motive force in circuit will be $4e$, and the resistance in circuit will be $\frac{4r}{3} + R$, for each series has a resistance of $4r$, and three parallel series connected at the ends are equivalent to a single series, of the same electro-motive force as one of the component series, and of one-third the resistance. The current will therefore be

$$C = \frac{4e}{\frac{4r}{3} + R} = \frac{12e}{4r + 3R} = \frac{e}{\frac{r}{3} + \frac{R}{4}}.$$

The question often arises, What is the best manner of grouping a given number of cells in order to give the strongest possible current through a given external conductor? The answer is, they should be so grouped that the internal and external resistance should be as nearly as possible equal; for example, if we have 12 cells as above, and the resistance R in the given conductor is $\frac{4}{3}$ of the resistance of one of these cells, the arrangement just described is the best.[1]

547. Divided Circuits.—When two or more wires are connected *in line*, that is so as to form one continuous wire, *the resistance of the whole is the sum of the resistances of the wires composing it.*

On the other hand, when two or more wires are arranged side by side, and connected at each end, so as to constitute so many independent channels of communication between the ends, the joint resistance is evidently less than the resistance of any one of the wires. When such an arrangement occurs in any part of a circuit, the circuit is said to be *divided.* If the several wires are of the same length and material, they act as one wire having a section equal to the sum of their sections, and the joint resistance is the quotient of the resistance of one of the wires by the number of wires. More generally, if the reciprocal of the resistance of a conductor be called its conducting power, *the conducting power of a system of wires thus connected at both ends is the sum of the conducting powers* of the several wires which compose it. Thus, in Fig. 471, if r_1, r_2 denote the resistances of the wires acb, adb, their joint resistance R will be given by the equation

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[1] Instead of 3 and 4, put x for the number of series, and y for the number of cells in a series. Then the current will be $\frac{e}{\frac{r}{x} + \frac{R}{y}}$, and will vary inversely as $\frac{r}{x} + \frac{R}{y}$. Now the product of $\frac{r}{x}$ and $\frac{R}{y}$ is given, being the quotient of rR by the whole number of cells; and when the product of two variables is given, their sum is least when they are equal, and increases as they are made more and more unequal. As x and y must be integers, exact equality cannot generally be obtained.

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2}, \quad \text{whence} \quad R = \frac{r_1 r_2}{r_1 + r_2}$$

547 A. Wheatstone's Bridge.—In any wire through which a current is flowing steadily, without leakage or lateral offshoots, the amount of the current is equal to the *difference of potential between the ends of the wire, divided by the resistance of the wire*, the units employed being the same as those which make $C = \frac{E}{R}$ for the whole circuit. The same thing is true for *any portion* of the length of such a wire, and, still more generally, for *any portion* of a circuit, whether single or divided, *terminated by equipotential cross-sections*, provided that no source of electro-motive force occurs in it. It follows that, in travelling along such a wire with the current, the fall of potential is proportional to the resistance travelled over, or *equal falls of potential occur in traversing equal resistances*. This rule does not apply to the comparison of the two independent channels of a divided circuit, unless equal currents are passing through them. It applies to the comparison of any two wires which are conveying equal currents, and it is not applicable to the comparison even of different portions of the same wire if, owing to leakage, the current is unequal at different parts of its length.

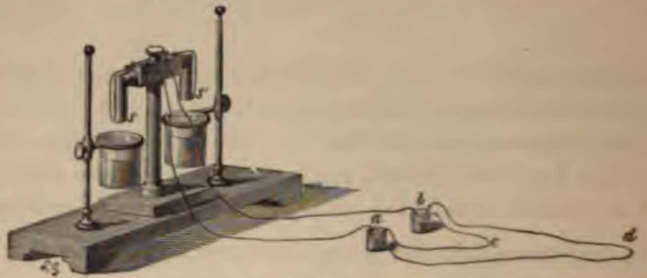

Fig. 471.—Divided Circuit.

Equality of potential in two points of a divided circuit can be tested by observing whether, when they are connected by a cross-channel, any current passes between them. This principle has been applied by Wheatstone, Thomson, and others, to the measurement of resistances, and the apparatus employed for the purpose is generally known as *Wheatstone's bridge*. It is typically represented in Fig. 471 A.

The poles P, N of a battery are connected by two independent channels of communication A C B, A D J E B. The former is a uniform wire; the latter consists of the wire D, whose resistance is to be determined, and of a standard resistance-coil E. The observation has for its immediate object to find what point in the uniform wire A B has the same potential as the junction J of the other two. When this point C is found, and connected with J through a galvanometer G, no current will pass across, and the needle of the galvanometer will not move. If a point C_1 on the positive side of C were connected with J, a current would run from C_1 to J, and if a point C_2 on the negative side were connected, the current would be from J to C_2. The deflection diminishes as the right point C is approached, and becomes reversed in passing it. When it is found, we know that the resistances in A C and C B have the same ratio as those of D and E, each of those ratios being in fact equal to the fall of potential between A and J C divided by the fall between J C and B. As the resistance of E is known, and the resistances of A C, C B are as their lengths, which are indicated on a divided scale, the resistance of D can be computed by simple proportion.

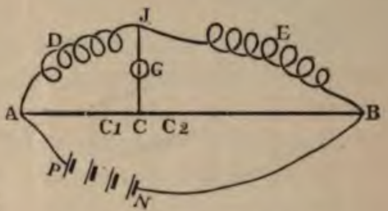

Fig. 471 A.—Wheatstone's Bridge.

In Wheatstone's original arrangement, the resistances of the two portions A C, C B were equal, and the resistances of the other two portions A D J, J E B were made equal by the help of a rheostat.

547 B. Difference of Potential of Poles of a Battery.—We have already stated that, when the poles of a battery are not connected, the difference of their potentials is a measure of the electro-motive force of the battery. On connecting them, this difference will be diminished, the diminution being greater as the resistance of the connecting wire is less. In fact, if the original difference of potential be divided into two parts, in the ratio of the external to the internal resistance, the first of these parts will be the fall of potential in the connecting wire (in other words, the difference of potential between the poles), and the second part will be the sum of the falls which occur in the liquids of the battery.

The annexed diagram (Fig. 471 B) represents the potentials in the different parts of a circuit consisting of a battery of four cells arranged as in Fig. 434, with its poles connected by a long wire whose resistance is *double* that of the battery.

The base-line AC represents the total resistance in circuit, AB being the resistance of the battery, and BC that of the connecting wire. We suppose the negative pole to be connected with the earth (which will not affect the current), so that its potential is zero. If any other part of the circuit be connected with the earth instead of this, the potentials here indicated must all be diminished by a constant quantity.

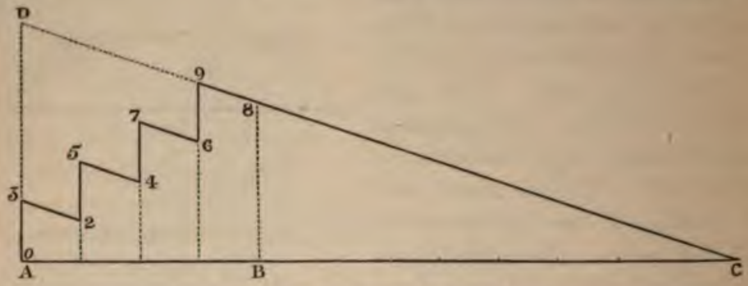

Fig. 471 B.—Curve of Potential for Closed Circuit.

The potential rises suddenly in passing from the first zinc to the acid in contact with it. Thence it falls gradually to the copper, which may be regarded as having the same potential with the part of the acid in contact with it, and also with the zinc of the second cell which is in metallic connection with it. These two suppositions are probably not quite correct, as there is reason to believe that some difference of potential always exists between dissimilar substances in contact, but for our present purpose these small differences may be neglected. Similar changes of potential occur in travelling through the other cells, and in each instance the gradual fall is one-third of the sudden rise (if the internal resistance of the battery be half the external). The distribution of potential may be stated in tabular form as follows, the electro-motive force of each cell being called 3:—

		Potential.
1st cell	Zinc,	0
	Acid,	3 to 2
	Copper,	2
2d cell	Zinc,	2
	Acid,	5 to 4
	Copper,	4
3d cell	Zinc,	4
	Acid,	7 to 6
	Copper,	6
4th cell	Zinc,	6
	Acid,	9 to 8
	Copper,	8
Connecting wire,		8 to 0

A D or twelve represents the whole electro-motive force of the battery; and if the external resistance were infinite, or if the poles were disconnected, the sloping lines marked 3,2 ; 5,4 ; 7,6 ; 9,8 ; would not be sloping but horizontal, and would have to be marked 3,3 ; 6,6 ; 9,9 ; 12,12.

547c. Measurement of Resistance of Battery.—The resistance of a battery may be measured in various ways, of which we shall only describe one.

Let the poles of the battery be directly connected with a galvanometer whose resistance is either very small or accurately known, and let the deflection be noted. Then let a wire of known resistance be introduced into the circuit, and the deflection again noted. The two currents thus measured will be inversely as the resistances, since the electro-motive force is the same in both cases. Let the resistance of the galvanometer coil be denoted by G, that of the wire introduced in the second case by W, and that of the battery by x. Then if the amounts of current be denoted by C_1, C_2, we have $\frac{C_1}{C_2} = \frac{x + G + W}{x + G}$; whence x can be determined.

548. Choice of Galvanometer.—The circumstances which should influence the choice of a galvanometer coil for a particular purpose, will now be intelligible. If stout wire is employed, the resistance is small, but it is not practicable to multiply convolutions to any great extent. Short coils of thick wire are accordingly employed in connection with thermo-piles, the resistance in the pile itself being so small that the total resistance in circuit is nearly proportional to the number of convolutions.

When, on the other hand, the resistance in the other parts of the circuit is very considerable, the resistance of the galvanometer coil becomes comparatively immaterial, so that, within moderate limits, the deflection of the needle is nearly proportional to the number of convolutions, and a coil composed of a great length of wire will give the maximum effect.

In both cases, for a given length and diameter of wire, the sensibility increases with the conductivity of the metal composing the wire. Copper is the metal universally employed, and its purity is of immense importance for purposes of delicacy, as impurities often increase its resistance by 50 or even 100 per cent.

549. Measurement of Electro-motive Force.—The most direct mode of comparing the electro-motive forces of cells of different kinds, would be to observe how many cells of the one kind arranged in series must be opposed to a given number of the other kind, in order that the resultant electro-motive force may be nil as indicated by the absence of deflection in a galvanometer forming part of the circuit. For example, if two Daniell's cells and one Grove's cell be connected with each other and with a galvanometer, in such a manner that the current due to the Daniell is in one direction, and that due to the Grove is in the opposite direction, the current actually produced will be in the direction of the greater electro-motive force. It will thus be shown whether the electro-motive force of a Grove's cell is more or less than double that of a Daniell's. This method has not been much used.

Another method of comparison consists in first connecting the two cells to be compared, so that their electro-motive forces tend the same way, and then again connecting them, so that they tend opposite ways, the resulting current being observed in both cases with the same galvanometer. The resistance in circuit is the same in both cases, being the resistance of the galvanometer plus the sum of the resistances of the cells; hence the currents will be simply as the electro-motive forces, that is to say, as E_1+E_2 to E_1-E_2, if E_1 and E_2 denote the electro-motive forces of the cells. Hence the ratio of E_1 to E_2 is easily computed.

Another method, which has been employed by Jules Regnault, is

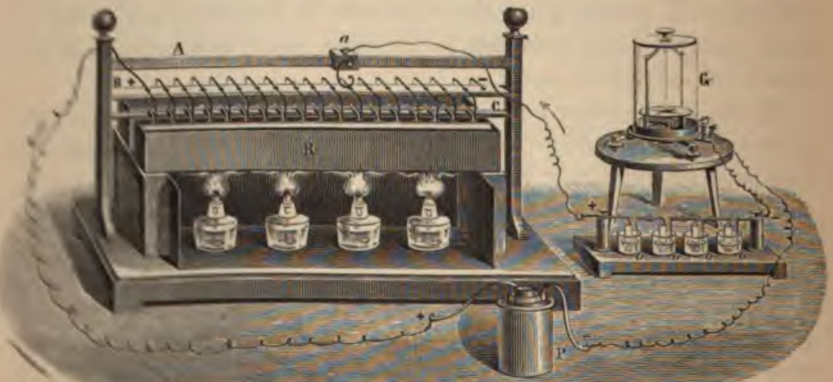

Fig. 472.—Jules Regnault's Apparatus.

illustrated by Fig. 472. It consists in balancing the electro-motive force of the cell P which is to be tested, by that of a series of thermo-electric elements, the number of which can be varied at pleasure. A is a thermo-electric pile, consisting of sixty elements of bismuth and copper, with their opposite junctions maintained at 0° and 100° C. Any number of these can be included in the circuit by moving the slider *a*, and the direction of the current which they tend to produce is opposite to that due to the cell P. As sixty thermo-electric elements would not be enough to balance one ordinary cell, some auxiliary cells *o o* of feeble electro-motive force, which has been previously determined, are employed to assist in opposing the cell P. It has thus been found that one Daniell's cell has the electro-motive force of about 174 of these thermo-electric elements.

Electro-motive force may also be measured statically by means of Thomson's quadrant electrometer, the poles of the battery being connected with the two chief electrodes of the instrument, in which arrangement no current will pass, and the electro-motive force will be directly indicated by the difference of potential observed.

According to Latimer Clark, the electro-motive forces of a cell of Grove, Bunsen, Daniell, and Wollaston are approximately as 100, 98, 56, and 46; but the last of these, being a one-fluid battery, is liable to fall off 50 per cent. or more, owing to the deposition of hydrogen on the copper plate.

CHAPTER XLVIII.

ELECTRO-DYNAMICS.

551. Meaning of Electro-dynamics.—A wire through which a current is passing, is found to be capable of producing movements in other wires also conveying currents. The theory of these movements, or more generally, of *the mechanical actions of currents upon one another*, constitutes a distinct branch of electrical science, and is called *electro-dynamics*. It stands in very close relation to electro-magnetism; and if the laws of either of the two sciences are given, those of the other may be deduced as consequences.

The science of electro-dynamics was founded by Ampère. Figs. 473, 474 represent an arrangement which he devised for rendering a conductor movable without interruption of the current conveyed by it.

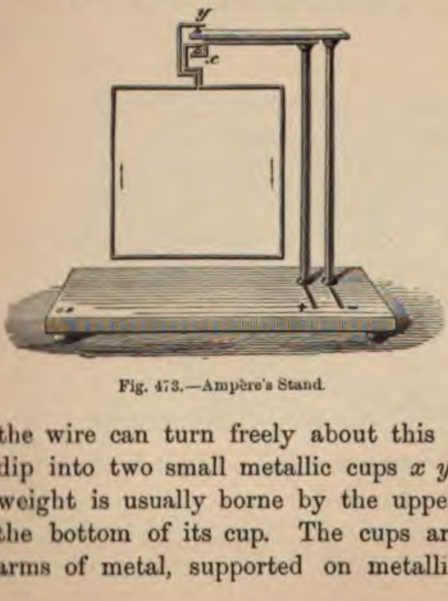

Fig. 473.—Ampère's Stand.

A wire is bent into the form of a nearly complete rectangle, and its two ends terminate in points, one above the other, so arranged that a vertical through the centre of gravity passes through them both. Accordingly, if either or both of these points be supported, the wire can turn freely about this vertical as axis. The points dip into two small metallic cups x y containing mercury, and the weight is usually borne by the upper point alone, which touches the bottom of its cup. The cups are attached to two horizontal arms of metal, supported on metallic pillars, which can be connected with the two terminals of a battery. The wire thus forms part of the circuit, the current being down one side of the rectangle and up the other. Instead of the rectangular the circular form may be employed, as in Fig. 475.

If a magnet be placed beneath, as in Fig. 474, the wire frame will set its plane perpendicular to the length of the magnet, the relative position assumed being the same as if the wire frame were fixed, and the magnet freely suspended, if we neglect the disturbing effect of the earth's magnetism.

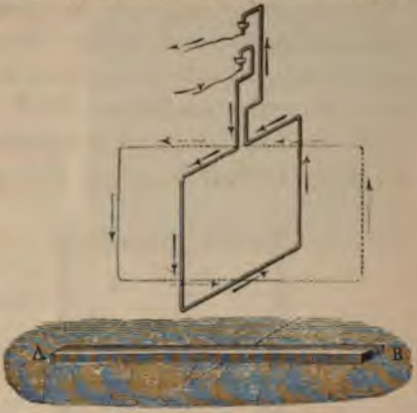

Fig. 474.—Action of Magnet on Movable Circuit.

552. Mutual Forces between Conductors conveying Currents.—The following elementary laws, regarding the mutual forces exerted between conductors through which currents are passing, were established by Ampère. For brevity of expression, it is usual to speak, in this sense, of the *mutual forces between currents*, or of the *mutual mechanical action of currents.*

I. *Successive portions of the same rectilinear current repel one another.*[1]

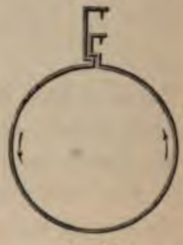

Fig. 475.

This is proved by the aid of two troughs of mercury separated by a partition (Fig. 476). A varnished wire is bent into such a form that two portions of it can float on the surface of the mercury in the two troughs, while connected with each other by an arc passing over the partition. The only portions without varnish are the ends. When the terminals of a battery are inserted in the mercury, opposite the ends, as shown in the figure, the circuit is completed through the wire, and repulsion is exhibited, the wire moving away to the further end of the vessel.

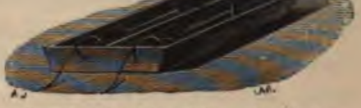

Fig. 476.—Repulsion of Successive Portions.

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[1] This first law is not universally accepted, and can scarcely be regarded as resting on the same sure foundation as the rest.

II. *Parallel currents, if in the same direction, attract, and if in the opposite direction, repel each other.*

The apparatus employed for demonstrating this twofold proposition, consists of two metallic pillars *t*, *v* (Fig. 477), which are respectively connected at their upper ends with the two cups of mercury *x*, *y*. The rectangular conductor *a b c d e* is suspended with its terminal points in these cups so as to complete the circuit between the pillars. When the current is passed, this movable conductor always places itself so that its plane coincides with that of the two pillars, and so that currents in the same direction in the pillars and in the wire are next each other, as shown in the figure.

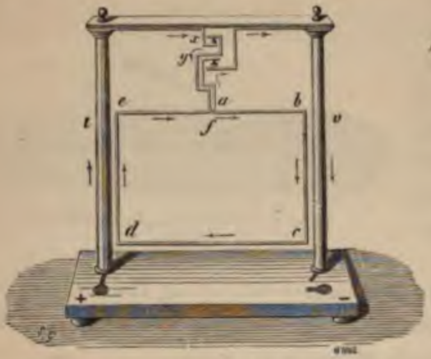

Fig. 477.—Attraction of Parallel Currents.

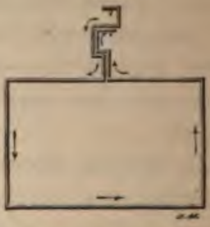

Fig. 478.—Apparatus for Repulsion.

For establishing repulsion, a slightly different form of wire is employed, which is represented in Fig. 478. When this is hung from the cups, in the position which the figure indicates, the currents in the pillars are in opposite directions to those in the neighbouring portions of the movable conductor, and the latter accordingly turns away until it is stopped by the collision of the wires above.

III. *Currents whose directions are inclined to each other at any angle, attract each other if they both flow towards the vertex of the angle,*[1] *or if they both flow from it, and repel each other if one of them flows towards the angle, and the other from it.*

A consequence of this law is that two currents, as A B, D C (Fig. 479), crossing one another near O in different planes, tend to set themselves parallel, and so that their directions shall be the same.

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[1] If the currents are not in the same plane, we must substitute *the feet of their common perpendicular* for *the vertex of the angle*, in the enunciation of this law.

For there is attraction between the portions AO and DO, and also between the portions OB and OC; whereas there is repulsion between AO and OC, and between OB and OD. Accordingly, if the movable conductor of Fig. 477 or 478 be traversed by a current, and another wire carrying a current be placed horizontally at any angle underneath its lower side, the movable conductor will turn on its point of suspension till it becomes parallel to the wire below it; and in the position of stable equilibrium the current in its lower side will have the same direction as that in the influencing wire.

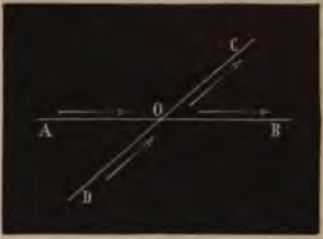

Fig. 479.—Tendency to set Parallel.

553. Continuous Rotation produced by a Circular Current.—Suppose we have a current flowing round a circle (Fig. 480), and also a current flowing along OA, which is approximately a radius of this circle. First let the current in OA be from the centre towards the circumference, as indicated in the figure. Then, by law III., OA is attracted on one side and repelled on the other, both forces combining to make OA sweep round the circle in the opposite direction to that in which the circular current is flowing. If the current in OA were from circumference to centre, the tendency would be for OA to sweep round the circle in the same direction as the circular current.

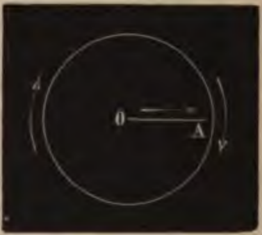

Fig. 480.—Continuous Rotation of Radial Current.

The reasoning still holds if OA is in a plane parallel to that of the circular current, O being a point on the axis of the circle and the length of OA being not greater than the radius.

A circular current may also produce continuous rotation in a conductor parallel to the axis of the circle, and movable round that axis. Fig. 481 represents an arrangement for obtaining this effect.

A coil of wire through which a current can be sent, is wound round the copper basin EF, its extremities being connected with the binding-screws *m*, *o*. From the centre of the basin rises the little metallic pillar A, terminating above in a cup containing mercury. This pillar is connected with the binding-screw *n*. The basin, which is connected with the binding-screw *p*, contains water mixed with a little acid to improve its conducting power, and a movable conductor BC rests, by a point, on the bottom of the cup of mercury, while its lowest portion, which consists of a light hoop, dips in the acidulated water. By connecting *m* and *n* a single circuit is obtained, of which *o* and *p* are the terminals, so that if *o* is connected with the positive and *p* with the negative pole of a battery, the current entering at *o* first traverses the wire coil, then ascends the pillar A, returns down the sides B, C to the floating ring and liquid, and so escapes to *p*. As soon as these connections have been completed, the movable conductor commences continuous rotation in the direction opposite to that of the current in the coil.

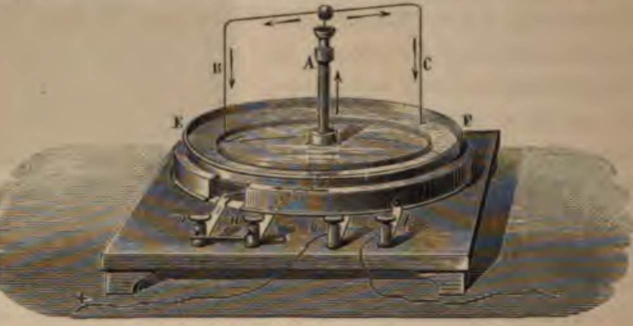

Fig. 481.—Apparatus for Continuous Rotation.

If, instead of connecting *m* and *n*, we connect *n* and *o*, and lead the positive wire from the battery to *p* and the negative wire to *o*, the course of the current will be from *p* to the acid, thence up the sides B, C, and inwards along the top of the movable conductor to the mercury cup, then down the pillar to *n*, thence to *o*, and through the coil from *o* to *m* in the same direction as in the former experiment; but the rotation of the movable conductor will now occur in the opposite direction to that before observed, and therefore in the same direction as the current.

554. Action of an Indefinite[1] Rectilinear Current upon a Finite Current movable around one Extremity.—A finite current movable about one extremity may also be caused to rotate continuously about this extremity by the action of an indefinite rectilinear current. This is clearly indicated by Fig. 482. In the right-hand diagram, the current O A flowing outwards from the centre of motion O, and acted on by the indefinite current M N, is first attracted into the position O A′. In this new position it is repelled by *n* N, and attracted by M *n*. It is thus brought successively into the positions O A″, O A‴, O A^{IV}. In this last-mentioned position, the two currents being parallel and opposite, there is repulsion; and after passing it, there is again repulsion on one side and attraction on the other, till it is carried round to its first position O A. It is thus kept in continual rotation. If the movable current flows inwards to the centre of motion O, as in the left-hand diagram, while the direction of the indefinite current is the same as before, the direction of rotation will be reversed.

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[1] The word *indefinite*, in this application, simply means *of great length in comparison with the distance and length of the movable current.*

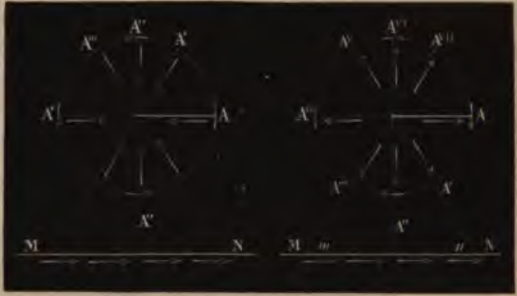

Fig. 482.—Rotation of Radial Current.

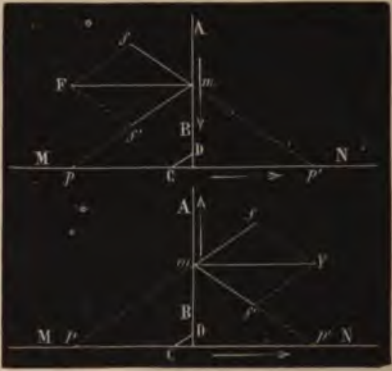

Fig. 483.—Translation Parallel to Indefinite Current.

555. Action of an Indefinite Rectilinear Current on a Finite Current Perpendicular to it.—Let M N, in the upper half of Fig. 483, be an indefinite rectilinear current, and A D a portion of another current either in the same or in any other plane. In the latter case let D C be the common perpendicular. Then, if the currents have the directions represented by the arrows, an element at *p* will attract an element at *m* with a force which we may represent by a line *m f′*; and an element at *p′* equal to that at *p* and situated at the same distance from C on the other side, will repel the element at *m* with an equal force, represented by *m f*. Constructing the parallelogram of forces, the resultant force of these two elements upon *m* is represented by the diagonal *m* F, which is parallel to M N and in the opposite direction to the indefinite current. As this reasoning applies to all the elements of both currents, it follows that the current AB will experience a force tending to give it a motion of translation parallel to MN. This motion will be opposite to the direction of the indefinite current when the direction of the finite current is towards the common perpendicular DC, as in the upper diagram, and will be in the same direction as the indefinite current when the direction of the finite current is from the common perpendicular, as in the lower diagram.

556. Action upon a Rectangular Current movable about an Axis Perpendicular to an Indefinite Current.—It follows from the preceding section that if a finite current AB (Fig. 484), perpendicular to an indefinite current, is movable round an axis O O′ parallel to itself, the plane A B O O′ will place itself parallel to the indefinite current, and AB will place itself in advance or in rear of the axis according as the current in A B is from or towards the indefinite current.

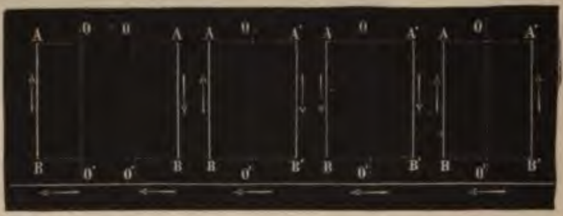

Fig. 484.—Position assumed by Perpendicular Current.

If a pair of parallel and opposite currents BA, A′B′, rigidly connected together, and movable round the axis O O′ lying between them, are submitted to the action of the indefinite current, the forces upon them will conspire to place the system in the position indicated in the figure. If the two currents A B, A′B′ are both in the same direction, their tendencies to revolve round the axis O O′ will counteract each other.

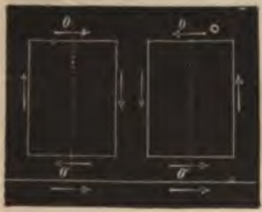

Fig. 485.—Position assumed by Rectangular Current.

557. Action upon a Rectangular Current movable round an Axis Perpendicular to an Indefinite Current.—If a rectangular current (Fig. 485) is movable round an axis *oo′* perpendicular to the direction of the indefinite rectilineal current, we have just seen that the action upon the two sides of the rectangle which are perpendicular to the latter, tends to place the system so that its plane shall be parallel to the indefinite current, and that the side which carries the receding current shall be in advance of the other. The action upon the near side of the rectangle contributes to produce the same effect, since this side tends to set itself parallel to the influencing current, and so that the directions of the two shall be the same.

The action upon the further side of the rectangle tends to produce an opposite effect; but, in consequence of the greater distance, this action is feebler than that upon the near side. The system accordingly tends to take the position of stable equilibrium represented in the right-hand half of the figure. The diagram on the left hand represents a position of unstable equilibrium.

What is here proved for a rectangular current, is true for any closed plane circuit movable round an axis of symmetry perpendicular to an indefinite rectilinear current; that is to say, any such circuit tends to place itself so that the current in the near side of it is in the same direction as the indefinite current.

The results of § 556 can be verified experimentally by the aid of the apparatus represented in Fig. 486. CC, DD are two cups (shown in section) surrounding the metallic pillar AB at its upper and lower ends, and containing a conducting liquid. The lower cup is insulated from the pillar, and connected with the binding-screw *g*. The liquid in the upper cup CC is connected with the upper end of the pillar by the bent arm *d m*. *o*K is a light horizontal rod supported on a point at B, and carrying a counterpoise K at one end, while the other carries a wire *mnop*, whose two ends *nm* and *op* descend vertically into the two cups, the middle portion of the wire being wrapped tightly round the rod. The binding-screw *f* is connected with the lower end of the pillar. If a current enters at *f* and leaves at *g*, its direction in the long vertical wire *op* will be descending; and it will be ascending, if the connections are reversed. By sending a current at the same time through a long horizontal wire in the neighbourhood of the system, movements will be obtained in accordance with the foregoing conclusions.

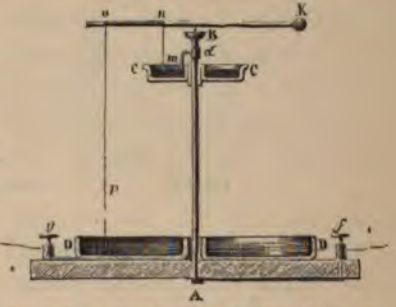

Fig. 486.—Position assumed by Vertical Current.

558. Sinuous Currents.—A sinuous current exhibits the same action as a rectilinear current, provided that they nowhere deviate far from each other. This principle can be exemplified by bringing near to a movable conductor (Fig. 487) another conductor consisting of a wire doubled back upon itself, having one of its portions straight, and the other sinuous, but very near the first. A current sent through this double wire traverses the straight and the sinuous portions in opposite directions, and it will be found that their joint effect upon the movable conductor is inappreciable.

This principle holds not only for rectilinear currents but for currents of any form, and is very extensively employed in the analytical investigations of electro-dynamics. In computing the action exercised by or upon a conductor of any form, it is generally convenient to substitute for the conductor itself an imaginary conductor, nearly coincident with it, and consisting of a succession of short straight portions at right angles to one another (Fig. 488).

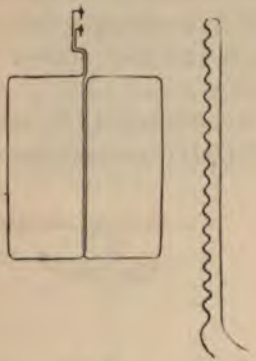

Fig. 487. Sinuous Currents.

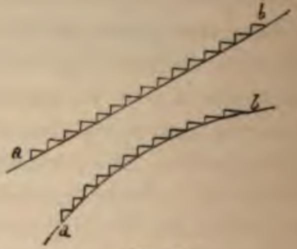

Fig. 488.

559. Mutual Action of Two Elements of Currents.—Ampère based his analytical investigations on the assumption that the action exercised by an element (*i. e.* a very short portion) of one current upon an element of another, consists of a single force directed along the joining line. This assumption conducted him to a formula for the amount of this force, which has been found to give true results in every case capable of being tested by experiment. Nevertheless, it is by no means certain that either Ampère's formula or his fundamental assumption is true. Other assumptions have been made, leading to other formulæ in contradiction to that of Ampère, which also give true results in every case capable of being experimentally tested.

The fact is that experiments can only be performed with complete circuits, and the contradictions which subsist between the different assumptions, in the case of the several parts of a circuit, vanish when the circuit is considered as a whole. All the formulæ, however, agree in making the mutual force or forces between two elements vary inversely as the square of their distance, and directly as the products of the currents which pass through them. Professor Clerk Maxwell[1] discards all assumptions as to mutual actions between elements at a distance, and employs the principle that a circuit conveying a current always tends to move in such a manner as to increase the number of magnetic force-tubes (in the sense of § 445 H) which pass through it. The work done in any displacement is measured by the number of tubes thus added; but tubes which cross the circuit in the opposite direction to those due to the current in the circuit are to be regarded as negative.

We have seen (§ 531 A, B) that the lines of magnetic force due to a current are circles surrounding it; and also that, when a line of magnetic force cuts a current, the latter experiences a force tending to move it at right angles to the plane of itself and the line of force. In the case of two parallel currents, each is cut at right angles by the lines of magnetic force due to the other; the direction of the force experienced by either current is therefore directly to or from the other current; and the criterion of § 531 B will be found to indicate attraction when the directions of the currents are the same, and repulsion when they are opposite.

In Fig. 480 the lines of magnetic force cut OA in a direction perpendicular to the plane of the diagram, OA accordingly experiences a force perpendicular to its own length in the plane of the diagram; and the same remarks apply to AB in Fig. 484. All the experimental facts above detailed are in fact thus explicable. In the experiment of Fig. 476, where the application is scarcely so obvious as in the other cases, the observed motion may be deduced from the direction in which the bridge or arc connecting the two side-wires is cut by the lines of force.[2]

560. Action of the Earth on Currents.—In virtue of terrestrial magnetism, movable circuits, when left to themselves, take up definite positions having well-marked relations to the lines of terrestrial magnetic force. For example, in the apparatus of Fig. 486, the vertical wire op will place itself to the west or east (magnetic) of the pillar AB, according as the current in op is ascending or descending. This effect is due to the horizontal component of terrestrial magnetism.

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[1] Maxwell "On Faraday's Lines of Force." Camb. Trans. 1858, p. 50.

[2] Some further remarks on the forces experienced by currents in magnetic fields will be found in Chap. lii.

In the apparatus of Fig. 481, if the current be sent only through the movable portion, continuous rotation will be produced, which will be with or against the hands of a watch according as the current in the top wires is inwards or outwards. This effect is due to the vertical component of the earth's magnetism, acting on the currents in the horizontal wires. Vertical lines of magnetic force falling on a horizontal current give the latter a tendency to move perpendicular to its own length in a horizontal plane.

561. Solenoids.—If we suspend from Ampère's stand (Fig. 473) a plane circuit, whether rectangular or circular, it will place itself perpendicular to the magnetic meridian, in such a manner that the current in its lower side is from east to west; or, in other words, so that the ascending current is in its western and the descending current in its eastern side; this effect being due to the action of the horizontal component of terrestrial magnetism upon the ascending and descending parts of the current. If, then, we have a number of such circuits, rigidly connected together at right angles to a common axis, and with their currents all circulating the same way, their common axis will tend to place itself in the magnetic meridian, like the axis of a magnet. Such a system was called by Ampère a solenoid (σωλήν, a tube), and was realized by him in the following manner.

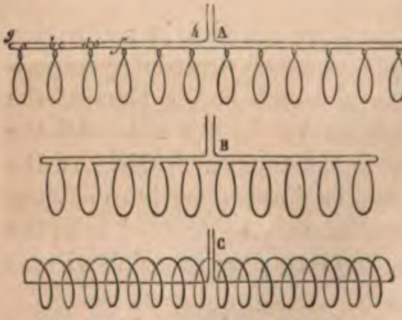


Fig. 491.—Solenoids.

Imagine a wire bent into such a shape as to consist of a number of rings united to each other by straight portions. It will differ from a theoretical solenoid only by having currents in these straight portions; but if the two ends of the wire be carried back till they nearly meet in the middle of the length, as shown at A and B (Fig. 491), the currents in these returning portions, being opposite to those in the other straight portions, will destroy their effect, and the resultant electro-dynamic action of the system will be simply due to the currents in the rings. The same effect is more conveniently obtained by substituting for the rings and intermediate straight portions, a helix, which, by the principles of sinuous currents, is equivalent to them. Each spire of the helix represents a circle perpendicular to the axis, together with a straight portion parallel to the axis and equal to the distance between two spires. The effect of all the straight portions is exactly destroyed by the wires which return from the ends of the helix and meet in the middle. This arrangement, which is represented at C, is that which is universally adopted, the returning wires being sometimes in the axis, and sometimes on the outside of the helix.

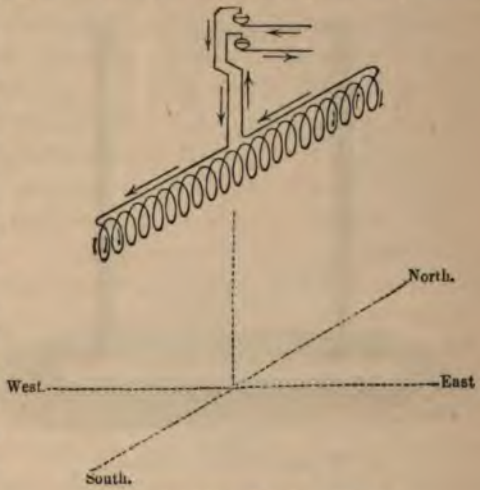


Fig. 492.—Orientation of Solenoid.

If a solenoid, thus constructed, be suspended on an Ampère's stand, as in Fig. 492, and a current sent through it, it will immediately place its axis parallel to a declination needle. It may accordingly be said to have poles. In Fig. 493, A represents the austral or north-seeking, B the boreal or south-seeking pole of the solenoid; that is to say, the direction of the current is against or with the hands of a watch according as the austral or boreal pole is presented to the observer. The same difference is illustrated by Fig. 492.

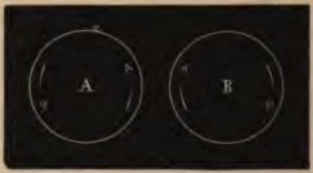


Fig. 493.—Poles of Solenoid.

562. Dip of Solenoid.—If a solenoid could be balanced so as to be perfectly free to move about its centre of gravity, it would place its axis parallel to the dipping-needle. The experiment would be scarcely practicable with a solenoid properly so called, on account of its weight; but it can be performed with a single plane circuit, such as that shown in Fig. 494. If such a circuit is nicely balanced about an axis through its centre of gravity, and placed so that it can turn freely in the plane of the magnetic meridian, the passing of a current through it will cause it to set its plane perpendicular to the direction of a dipping-needle. This effect is due to the action of terrestrial magnetism on the upper and lower sides of the rectangle. The plane of the rectangle is represented in the figure as coinciding with the direction of dip. In this position the action of terrestrial magnetism urges the upper side backwards, and the lower side forwards, and stable equilibrium will be attained when the rectangle has turned through 90°.

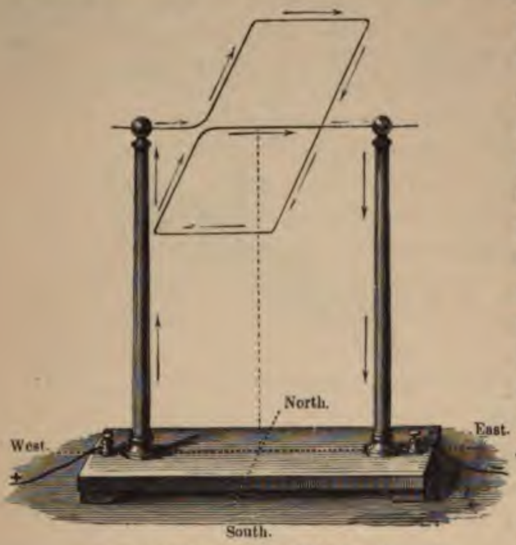


Fig. 494.—Dip of Element of Solenoid.

563. Mutual Actions of Solenoids.—Solenoids behave like magnets not only as regards the forces which they experience from terrestrial magnetism, but also as regards the actions which they exert upon one another. The similar poles of two solenoids repel, and the unlike poles attract each other, as we may easily prove by suspending one solenoid from an Ampère's stand and bringing another near it.

The reason of these attractions and repulsions is illustrated by Fig. 495. If two austral poles are placed opposite each other, as in the upper part of the figure, the currents are circulating round them in opposite directions, and, by the laws of parallel currents, should therefore repel each other; whereas if two dissimilar poles be placed face to face, the currents which circulate round them are in the same direction, and attraction should therefore ensue.

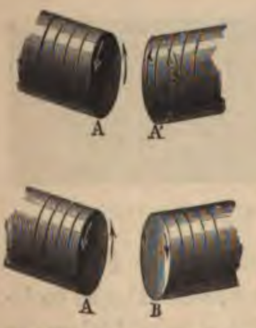


Fig. 495.—Mutual Action of Solenoids.

Lastly, if one pole of an ordinary magnet be brought near one pole of a suspended solenoid, as in Fig. 496, repulsion or attraction will be exhibited according as the poles in question are similar or dissimilar. In the position represented in the figure, this action is mainly due to the action of the boreal pole of the magnet upon the descending currents in the near side of the solenoid. This action consists in a force to the left hand, nearly parallel to the axis of the solenoid, which tends to make the solenoid rotate about its supports, and thus to bring the end A of the solenoid into contact with the end B of the magnet.

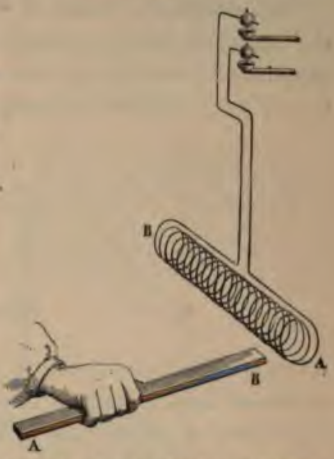


Fig. 496.—Action of Magnet on Solenoid.

It may be shown, by the aid of Ampère's formula for the mutual force between two elements, that the mutual action of two solenoids is equivalent to four forces, directed along lines joining the poles of the solenoids, and varying inversely as the squares of the distances between the poles; the forces between similar poles being repulsive, and the other two attractive. The analogy between solenoids and magnets is thus complete.

564. Astatic Circuits.—When it is desired to eliminate the influence of terrestrial magnetism in electro-dynamic experiments, an astatic circuit may be employed as the movable conductor. Two such circuits are represented in the accompanying figures (Figs. 497, 498). In each of them the current in one half of the circuit circulates with,

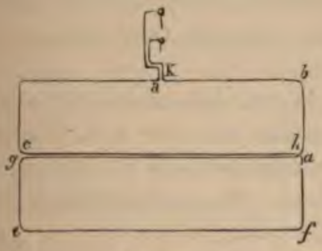


Fig. 497.

Astatic Circuits.

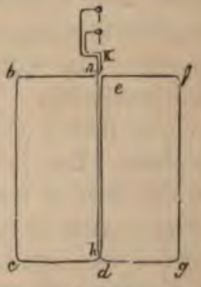


Fig. 498.

and in the other against the hands of a watch, thus producing equal and opposite tendencies to orientation, which destroy one another.

565. Ampère's Theory of Magnetism.—In accordance with the preceding facts, Ampère propounded the hypothesis that what is called magnetism consists in the existence of electric currents circulating round the particles of magnetic bodies. In iron or steel, when unmagnetized, according to this theory, the currents around different particles have different directions; but when it is magnetized, the directions of all are the same. Fig. 499 represents an ideal section of a magnetized bar at right angles to the direction of its magnetization. On the neighbouring faces of any two particles, the currents are in opposite directions, hence, by the laws of sinuous currents, there is a mutual destruction of force through the whole interior, and the resultant effect is the same as if there were currents circulating round the exterior of the magnet, as represented in Fig. 500.

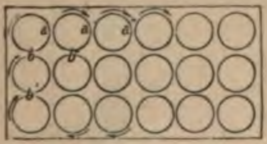
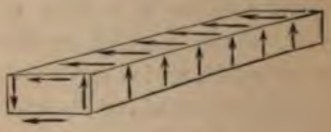


Fig. 499.



Amperian Currents in Magnet. Fig. 500.

Magnetization by influence depends, according to this theory, on the tendency of currents to set themselves parallel and in similar directions; and if the substance magnetized possesses coercive force, the direction thus impressed on its currents persists after the influence is removed. In soft iron, on the contrary, they resume their former irregularity.

Ampère's theory of magnetism is in complete accordance with all known facts. But it admits of question whether it is simpler to deduce the laws of magnetism and electro-magnetism from those of electro-dynamics; or to adopt the reverse order, and deduce the laws of electro-dynamics from those of electro-magnetism.

566. Rotation of a Magnet on its Axis.—The following experiment is due to Ampère. A magnet, loaded with platinum at its lower end, floats upright in mercury contained in a glass vessel (Fig. 501). A cavity is hollowed out in the top of the magnet. This contains mercury, in which a point dips. On connecting one of the terminals of a battery with this point, and the other with the outer edge of the mercury in the vessel, the magnet is seen to rotate on its axis. If the north-seeking pole is uppermost, and the positive pole of the battery is connected with the point, the direction of rotation is N.E.S.W.

The Amperian explanation of this phenomenon is, that it is due to the action between the outward-flowing current in the mercury and the Amperian currents which circulate round the magnet. The latter, as represented by the arrows n C, C m in Fig. 502, are opposite to watch-hands. The outward-flowing current in CD attracts the current in C m, since they are both directed away from the angular point C, and repels the current in n C. Hence the magnet is made to rotate in the direction m C n, opposite to that of the Amperian current.

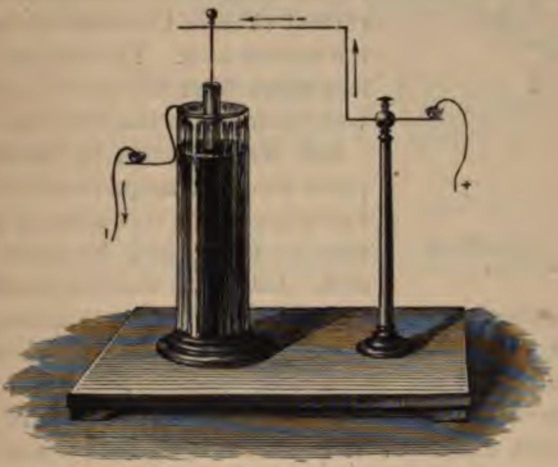


Fig. 501.—Rotation of Magnet.

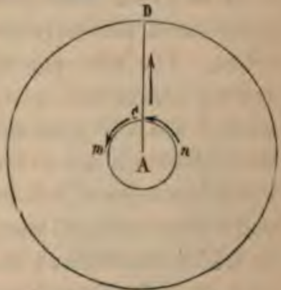


Fig. 502.—Explanation of Rotations.

The experiment is sometimes varied by making the point dip in the mercury in the vessel, the magnet being allowed to float freely near it, and a metallic ring being immersed at the outer edge of the mercury, to which the current flows out in all directions from the point. As soon as the circuit is completed, the magnet begins to revolve round the point. The rotation will be in the same direction as in the other form of the experiment; that is to say, if the current flows outwards from the point to the edge of the vessel, the direction of rotation will be opposite to that of the Amperian currents in the magnet. This is easily explained by the laws of parallel currents, for the current in OC (Fig. 503) attracts the Amperian current at *m*, and the current in O D repels the current at *n*. The magnet will therefore move from OD to OC, and will revolve round O in the direction N.E.S.W.

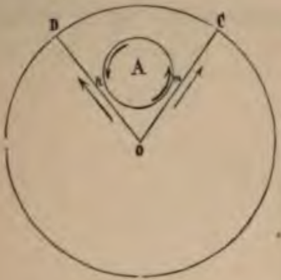


Fig. 503.—Explanation of Rotations.

567. Magnetization by Currents.—Ampère's theory of magnetism leads naturally to the conclusion that a bar of iron or steel may be magnetized by means of a current. Arago was the first to establish this fact, but without a clear apprehension of the conditions necessary for success, or of the criterion for determining which will be the austral, and which the boreal pole. Ampère conceived the idea of introducing the needle to be magnetized into the axis of a solenoid, and the result confirmed his prediction that the poles of the needle would be turned the same way as those of the magnetizing helix. This is what must happen if the currents in the helix force the Amperian currents in the bar into parallelism with themselves, so that all rotate the same way. The action, in fact, is precisely analogous to that represented in Fig. 477.

It is to be remarked that, in this process of magnetization, the portions of the currents parallel to the axis of the helix produce no effect. The wire through which the current is to be sent may be wound like thread upon a reel, returning alternately from end to end, and all the convolutions will contribute to magnetize the bar the same way, although it is evident that the helices are in this case alternately right-handed and left-handed. The north-seeking and south-seeking poles may be in all cases distinguished by the rule that the direction in which the current circulates in the coil is against watch-hands as seen from the former and with watch-hands as seen from the latter; or it may be remembered by the rule, that if I identify my own body in imagination with a portion of the wire, and suppose the current to enter at my feet, while my face is towards the needle, the north-seeking pole will be to my left. In 1 and 2 (Fig. 504) *a* will be the austral (or north-seeking), and *b* the boreal pole of the inclosed needle, when the current in the helix has the direction indicated by the arrows.

If the direction of winding is changed, in the manner represented in 3, so that, as seen from one end, the direction in which the current circulates is in one part with and in another against the hands of a watch, consequent points (§ 503) will be formed at the points of change. Thus, if the current enters at the left-hand end of the coil, the points *a a* will be austral, and the points *b b* boreal poles.

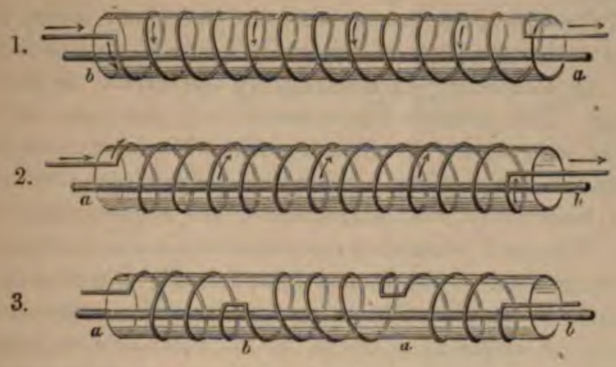


Fig. 504.

1. Right-handed Helix. 2. Left-handed Helix. 3. Arrangement for Consequent Points.

568. Electro-magnets.—Arago was the first to observe the effect of a current in magnetizing soft iron. On plunging in iron-filings a wire through which a very strong current was passing, he observed that the filings clung to the wire, that they placed their length tangentially to it, and that they fell off when the current ceased to pass. Each filing was evidently, in this experiment, a little magnet placing itself at right angles to the current. A cylindrical bar of iron can be powerfully magnetized by wrapping round it a coil of insulated wire and sending a current through this coil. Stout copper wire is generally employed for this purpose. Such an arrangement is called an *electro-magnet*.

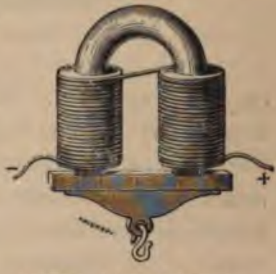


Fig. 505.—Horse-shoe Electro magnet.

The bar has often the horse-shoe form, as in Fig. 505, and in this case the central part is usually left bare. The direction of winding on the ends must be such that, if the bar were straightened out, the current would circulate in the same direction round every part. This is clearly shown in the figure. Electro-magnets have been constructed capable of sustaining a load of many tons.

Besides the enormous power that can be given them, electro-magnets have the advantage of being readily made or unmade instantaneously, by completing or interrupting the circuit to which the coil belongs. This principle has received very numerous and varied applications, some of which will be mentioned in later chapters.

569. Residual Magnetism.—When the current round an electro-magnet is interrupted, the destruction of the magnetization is not complete. The small remaining magnetization is called *remanent* or *residual* magnetism. It is frequently sufficiently powerful to retain the armatures in contact with the magnet, and thus necessitates the employment of *opposing springs*, if instantaneous separation is desired. The mere act of separation suffices to destroy the greater part of the residual magnetism.

Fig. 507 represents an electro-magnet EE′, furnished with an opposing spring g. The armature A, with its lever t, turns about the axis V V′. The opposing spring g has one end fixed at K, and the other attached to the end of the lever t. It therefore tends to remove the armature from the magnet. c and d are two points whose distance can be regulated, and which serve to limit the movements of the armature.

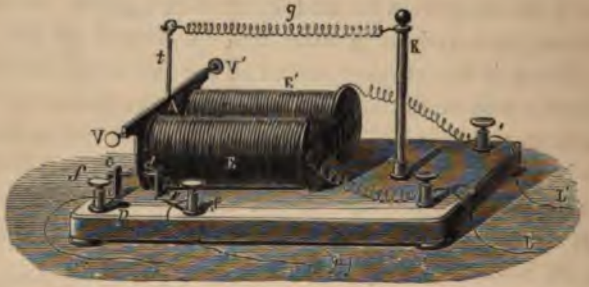


Fig. 507.—Electro-magnet with Opposing Spring.

CHAPTER XLIX.

HEATING EFFECTS OF CURRENTS.

570. Heating of Wires.—The heating of a wire by the passage of a current may conveniently be exhibited by the aid of the apparatus represented in Fig. 508. Two uprights mounted on a stand are furnished, at different heights, with pairs of insulated binding-screws aa', bb', cc', having wires stretched between them. A current can thus be sent through any one of the wires, by connecting the terminals of a battery with the binding-screws at its extremities. When this is done with a battery of suitable power, the wire is first seen to droop in consequence of expansion, then to redden, and finally to melt, becoming inflamed if the metal is sufficiently combustible.

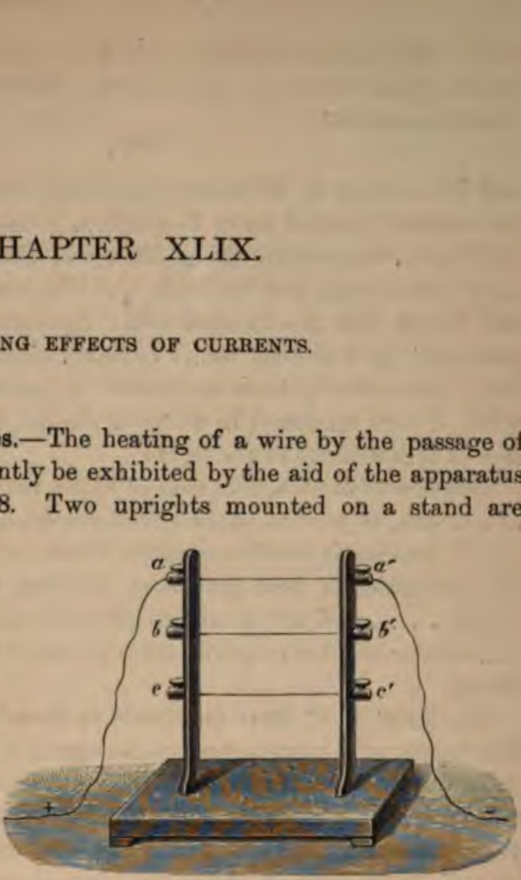


Fig. 508.—Stand for Heating Wires.

If a file is attached to one of the terminals of a battery, and the other terminal is drawn along the file, a rapid succession of sparks will be obtained; and if the battery be sufficiently powerful, globules of incandescent metal will be scattered about with brilliant effect.

571. Joule's Law.—The energy of a current is jointly proportional to the quantity of electricity that passes and the electro-motive force that drives it. As the numerical measure of a current is the quantity of electricity which passes in unit time, it follows that the energy of a current C lasting for a time t, is ECt, E denoting the electro-motive force. But again, by Ohm's law, E is equal to the product of the current C and the whole resistance R. The expression for the energy therefore becomes

$$C^2 R t, \qquad (1)$$

and this energy is all transformed into heat in the circuit, unless the current is called upon to perform some other kind of work in addition to overcoming the resistance of the circuit. It has accordingly been found, first by Joule, and afterwards by Lenz, Becquerel, and others, that the formula $C^2 R t$ represents the quantity of heat generated by a current under ordinary circumstances. The experiments have usually been conducted by passing a current through a spiral of wire immersed in water or alcohol, and observing the elevation of temperature of the liquid.

This law of Joule's, like that of Ohm, may be applied to any part of a circuit, as well as to the circuit considered as a whole; that is to say, if the circuit consists of parts whose resistances are $r_1, r_2, \ldots$, the quantities of heat generated in them are respectively $C^2 r_1 t$, $C^2 r_2 t, \ldots$, and are therefore proportional to the resistances $r_1, r_2 \ldots$ of the respective parts, since C and t are necessarily the same for all.

572. Relation of Heat in Circuit to Chemical Action in Battery.— The energy of a current, and consequently the heat developed in the circuit, is the exact equivalent of the potential energy of chemical affinity which runs down in the cells of the battery. This fact, first verified approximately by Joule, has been more accurately confirmed by the experiments of Favre, who introduced into the muffle of his mercurial calorimeter, already described and figured in § 351, a small voltaic cell with its poles connected by a fine wire. He found that the consumption of 33 grammes of zinc in the cell corresponded to a generation of heat amounting to 18,796 gramme-degrees. But the chemical action in the cell is complex. The 33 grammes of zinc unite with 8 grammes of oxygen, and in so doing generate 42,451 gramme-degrees. The combination of these 41 grammes of oxide of zinc with 40 grammes of sulphuric acid, produces 10,456 gramme-degrees, making in all 52,907. But an equivalent of water undergoes decomposition, and this *absorbs* 34,463, which must be subtracted from the above sum, leaving 18,444 gramme-degrees as the balance of heat generated in the whole complex action. The heat actually observed in the experiment, agreed almost precisely with this calculated amount.

573. Distribution of Heat in Different Parts of Circuit.—These experiments also served to verify the application of Joule's law to each part of the circuit considered separately. By introducing the cell into the muffle whilst a spiral of fine wire connecting the poles was outside, and then introducing the spiral while the cell was outside, Favre was able to measure separately the heat generated in the cell and in the spiral, and these were found to be proportional to their resistances.

If wires of different diameter or of different electrical conductivity form parts of the same circuit, so as to be traversed by the same current, the bad conductors will become more heated than the good, and the fine wires more than the coarse. All parts of the length of a uniform wire will be uniformly heated. The specific resistance of platinum is ten times greater than that of copper; hence ten times as much heat will be generated in a platinum as in a copper wire by a given current, if the diameters of the two wires be the same.

The *elevation of temperature* is greater in a fine than in a coarse wire, not only because of its greater resistance, which leads to the development of a greater quantity of heat in it, but also on account of its smaller capacity for heat, and its smaller surface. When the current is passed for so short a time that the heat emitted may be neglected, the elevation of temperature varies directly as the resistance per unit length, and inversely as the capacity per unit length. Each of these quantities varies directly as the section of the wire, and hence the elevation of temperature is inversely as the square of the section, or as the fourth power of the diameter.

On the other hand, if the current be continued till the permanent temperature is attained, capacity ceases to have any influence, and the heat emitted in unit time must be equal to the heat received. If x denote the elevation of temperature, the heat emitted is approximately $2\pi r B x$ by Newton's law (§ 307), B being a constant. The heat received is $\frac{A}{\pi r^2}$, A being another constant. By equating these two expressions, we find that $r^3 x$ is equal to a constant, and hence x varies inversely as r^3, that is, the elevation of temperature is inversely as the cube of the diameter.

To obtain the most rapid production of heat in the circuit considered as a whole, we must reduce the resistance to a minimum; for the heat produced in unit time is EC, which, by Ohm's law, is the same as $\frac{E^2}{R}$, and therefore varies inversely as R the total resistance.

574. Mechanical Work done by Current.—Favre's experiments also furnished a confirmation of the fact, that when a current is called upon to perform mechanical work, the amount of heat generated in the circuit is diminished by the equivalent of this work. He inclosed a battery of five cells in the muffle of one calorimeter, and an electro-magnet in another calorimeter, the connections between the coil of the electro-magnet and the poles of the battery being made by short thick wires whose resistance could be neglected. The electro-magnet attracted an armature, and thus raised a weight by means of external pulleys.

It was found that when the armature was fixed, so that no mechanical work could be performed, the heat developed was the precise equivalent of the chemical action which took place in the battery; but when the electro-magnet was allowed to raise the weight, the amount of heat indicated by the calorimeters was sensibly less. The difference was measured, and compared with the work done in raising the weight. The comparison indicated 444 kilogrammetres of work for each kilogramme-degree of heat that disappeared, a result which agrees sufficiently well with the established value of Joule's equivalent (425 kilogrammetres).

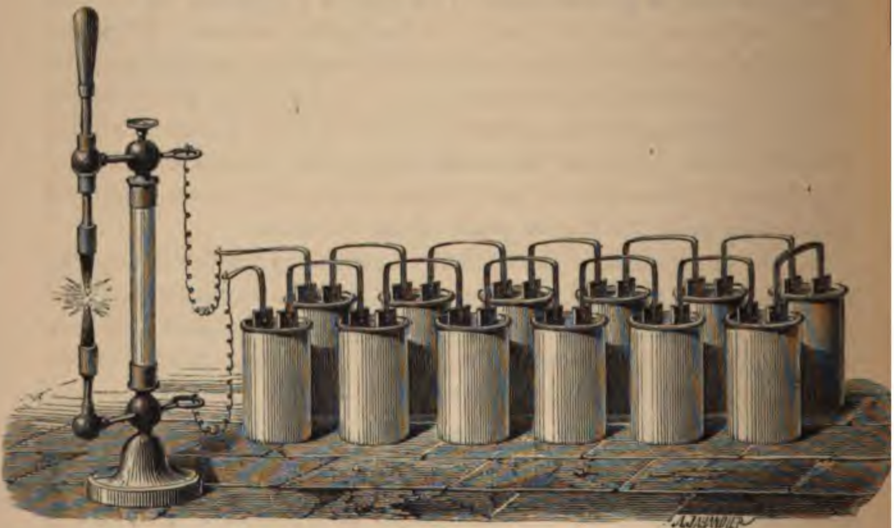


Fig. 509.—Electric Light.

575. Electric Light.—When two pointed pieces of a conducting kind of carbon, such as that which is deposited in the retorts at gas-works, are connected with the poles of a powerful battery, as in Fig. 509, a brilliant light is obtained by bringing them together so as to allow discharge to take place between them. This discharge, when once obtained, will not be interrupted by separating the points to some distance,—greater in proportion to the electro-motive force of the battery; and the interval will be occupied by a luminous arch (known as the *voltaic arc*) of intense brightness and excessively high temperature. This brilliant experiment was first performed by Sir Humphrey Davy, at the commencement of the present century, with a battery of 3000 cells. The light appears to be mainly due to the incandescence of particles of carbon which traverse the space between the points.

This transport of particles can be rendered visible to a large number of spectators by throwing an image of the heated points on a screen with the aid of a lens. Fig. 510 represents the image thus obtained, the natural size of the carbons being indicated by the sketch at the right hand. On watching the image for some time, incandescent particles will be observed traversing the length of the arc, sometimes in one direction and sometimes in the other, the prevailing direction being, however, that of the positive current. This circumstance, which appears to be connected with the higher temperature of the positive terminal, explains the difference between the forms assumed by the two carbons. The point of the positive carbon becomes concave, while the negative carbon remains pointed and wears away less rapidly. This difference is more precisely marked when the experiment is performed *in vacuo;* a kind of cone then grows up on the negative carbon, while a conical cavity is formed in the positive carbon. These phenomena are less clearly exhibited in air, on account of the combustion occasioned by the presence of oxygen.

The voltaic arc exceeds in temperature as well as in brightness all other artificial sources of heat. Despretz succeeded by its means in fusing and even volatilizing many substances which had previously proved refractory. Carbon itself was softened and bent, welded, and apparently reduced to vapour, which was condensed, in the form of black crystalline powder, on the walls of the containing vessel.

The voltaic arc must be regarded as an instance of conduction rather than of disruptive discharge, the air being rendered a conductor by the high temperature to which it is raised. Hence it is that, although discharge does not commence between the points till they have been brought close together, it is not interrupted by subsequently removing them to a considerable distance.

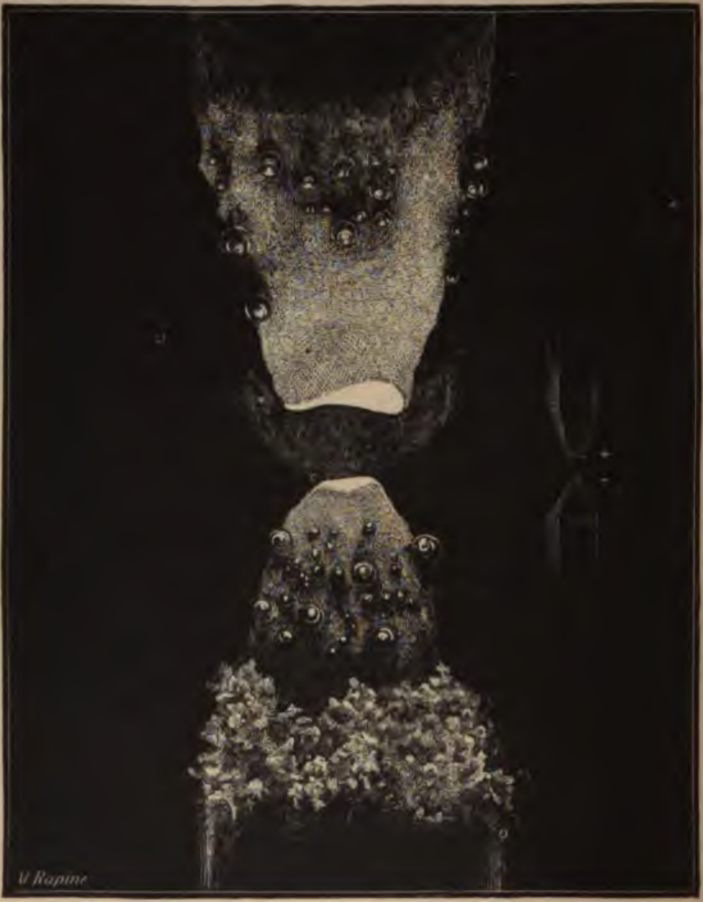


Fig. 510.—Image of the Carbon Points.

The voltaic arc is acted on by a magnet, according to the same laws as any other current. M. Quet, by employing a very powerful electro-magnet, with its poles at equal distances on opposite sides of the line joining the points, repelled the arc laterally to such an extent that it resembled a blowpipe flame (Fig. 511).

576. Light of the Voltaic Arc.—The light of the voltaic arc has a dazzling brilliancy, and attempts were long ago made to utilize it

The failures of these attempts were due not so much to its greater costliness in comparison with ordinary sources of illumination, as to the difficulty of using it effectively. Its brilliancy is painfully and even dangerously intense, being liable to injure the eyes and produce headaches. Its small size detracts from its illuminating power —*it dazzles rather than illuminates*— and it cannot be produced on a sufficiently small scale for ordinary purposes of convenience. There is no mean between the absence of light and a light of overpowering intensity.

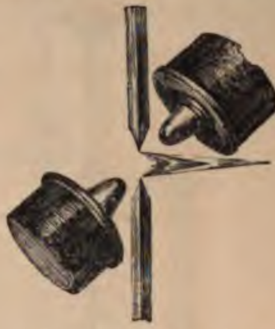


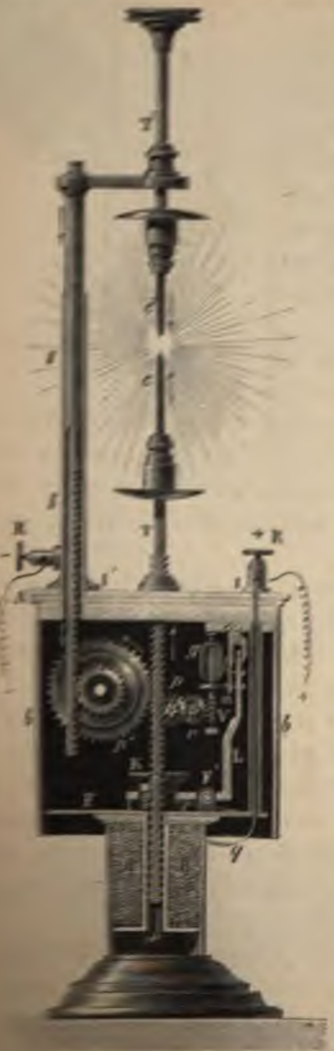
Fig. 511.—Action of Magnet on Voltaic Arc.

There is, however, one application in which these peculiarities of the electric light are positive advantages, penetration being the essential requisite; we mean the lighting-up of lighthouses. Here the office of the light is not to render other objects visible, but to be itself seen; and in this respect, in hazy weather, the electric light is found decidedly superior to oil-lamps.

The electric light is also extensively used for throwing images on a screen in lecture-illustrations, and for producing various luminous effects in theatrical exhibitions. It has also been successfully employed for enabling labourers to carry on their work at night.

As the carbons undergo waste by combustion, it is necessary to employ some means for keeping them at a nearly constant distance, so as to give a steady light. Several different regulators have been employed for this purpose, all of them depending on the principle that the strength of the current diminishes as the distance, and consequently the resistance, increases. We will briefly describe two, those of Duboscq and Foucault.

577. Duboscq's Regulator.—In Duboscq's apparatus (Fig. 512) there is a train of wheel-work, driven by a main-spring contained within the barrel P, the motion being moderated by means of the revolving fans *g*. The two racks S and T are driven by two wheels attached to the barrel, one of them (the driver of T) having double the radius of the other. One rack thus rises, and the other falls, but the rising rack T moves twice as fast as the other. The rack T is that which carries the positive carbon *c*; the negative carbon *c′* is fixed to the piece T′, which travels with the rack S. It has been found by experience that the positive carbon wears away twice as fast as the negative. Hence the adoption of this arrangement, which causes the positive carbon to move double the distance of the other. If the current were generated, not by a battery, but by a magneto-electric machine, such as we shall describe in a later chapter, each carbon would be alternately positive and negative, and it would be necessary to make their velocities equal.



[illegible]'s Regulator.

The current from the battery enters the apparatus by the binding-screw R, traverses the coil of the electro-magnet B B, whence it passes through the rack T to the positive carbon c. From the negative carbon c' it travels to the rack S, and escapes by the binding-screw R'. The soft-iron core[1] of the electro-magnet attracts an armature K, with a force which depends on the strength of the current. The armature is attached to one arm of the bent lever L, which turns about a horizontal axis at F', and an opposing spring s resists the attraction of the electro-magnet. The upper end of the bent lever governs the movements of a shorter lever l which turns about an axis at o. This short lever is armed at its lower end with a tooth or pallet m, whose office is to stop the movement of a toothed wheel, attached to the axis of the revolving fans.

When the current is passing in full strength, the electro-magnet [illegible] the armature, thus causing the pallet to lock the teeth of the wheel and hinder the machinery from moving; but as the carbons burn away, the resistance increases, the current diminishes, and the strength of the electro-magnet falls off, until the opposing spring is able to overpower it and raise the armature. This unlocks the pallet from the wheel, and the racks are accordingly driven forward, thus bringing the carbons nearer together, and increasing the current until the electro-magnet acquires sufficient power to prevail over the opposing spring and lock the wheel-work again.

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[1] [illegible] electro-magnet is the soft iron in its interior, which becomes magnetized [illegible]

A small lever is provided, for stopping or starting the motion by hand. The armature can also be screwed up or down, so as to regulate its minimum distance from the electro-magnet according to the battery power employed. The mechanism is inclosed in a metallic box, one side of which can be removed when it is desired to obtain access to the interior.

578. Foucault's Regulator.—Foucault's latest form of regulator differs from Duboscq's in having two systems of wheelwork, one for bringing the carbons nearer together, and the other for moving them further apart. Fig. 513 represents the apparatus, with the omission of a few intermediate wheels. L′ is a barrel driven by a spring inclosed within it, and driving several intermediate wheels which

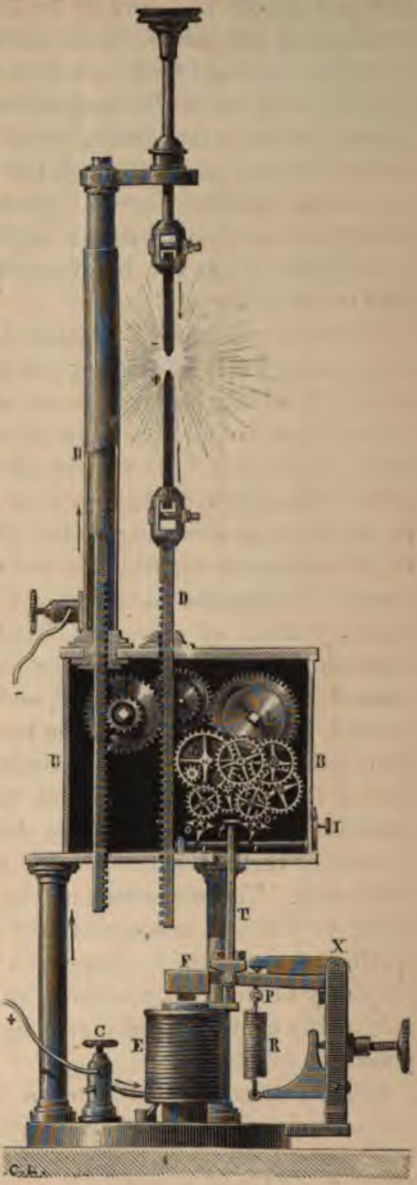

Fig. 513.—Foucault's Regulator.

transmit its motion to the fly *o*. L is the second barrel, driven by a stronger spring, and driving in like manner the fly *o′*. The racks which carry the carbons work with toothed wheels attached to the barrel L′, the wheel for the positive carbon having double the diameter of the other, as in Duboscq's arrangement above described. The current enters at the binding-screw C, traverses the coil of the electro-magnet E, and passes through the wheel-work to the rack D, which carries the positive carbon. From the positive carbon it passes through the voltaic arc to the negative carbon, and thence, through the support H, to the binding-screw connected with the negative pole of the battery.

When the armature F descends towards the magnet, the other arm of the lever F P is raised, and this movement is resisted by the spiral spring R, which, however, is not attached to the lever in question, but to the end of another lever pressing on its upper side and movable about the point X. The lower side of this lever is curved, so that its point of contact with the first lever changes, giving the spring greater or less leverage according to the strength of the current. In virtue of this arrangement, which is due to Robert Houdin, the armature, instead of being placed in one or the other of two positions, as in the ordinary forms of apparatus, has its position accurately regulated according to the strength of the current. The anchor T*t* is rigidly connected with the lever F P, and follows its oscillations. If the current becomes too weak, the head *t* moves to the right, stops the fly *o′* and releases *o*, which accordingly revolves, and the carbons are moved forward. If the current becomes too strong, *o* is stopped, *o′* is released, and the carbons are drawn back. When the anchor T*t* is exactly vertical, both flies are arrested, and the carbons remain stationary. The curvature of the lever on which the spring acts being very slight, the oscillations of the armature and anchor are small, and very slight changes in the strength of the current and brilliancy of the light are immediately corrected. The details of the mechanism contain some ingenious devices, which our limits do not permit us to explain.

578A. Peltier Effect.—When a current is sent through a heterogeneous circuit, a peculiar thermal effect occurs at each junction. We have seen, in Chap. xlv., that the heating of a junction in such a circuit tends to produce a current in a definite direction. It was discovered by Peltier that if a current be sent through the junction *in that direction*, the junction will be *cooled* by it, and that it will be warmed by a current sent in the opposite direction.

If, for example, a current from a battery is sent through an ordinary thermo-pile, the junctions at one end will rise in temperature, and those at the other end will be depressed. If the battery be then removed, and a galvanometer substituted, a current in the opposite direction to the former will be indicated by the galvanometer, until equality of temperature has been restored.

The *Peltier effect,* as it is called, is superadded to the general warming due to the overcoming of resistance in the circuit, so that the actual temperature attained by a junction depends on both causes combined.

CHAPTER L.

ELECTRO-MOTORS—TELEGRAPHS.

579. Electro-magnetic Engines.—Electro-magnetic engines are driven by means of the temporary magnetization of soft iron under the influence of a current. This magnetization can be destroyed or reversed with great rapidity; and it is thus possible to produce alternate movements of an armature, which can be readily transformed into other movements by ordinary mechanism. Since 1834, when Jacobi of St. Petersburg constructed the first engine of this kind, many other inventors have tried their powers in the same direction; but none of these attempts have been commercially successful, and the idea of employing such engines for any useful purpose is now almost abandoned.

The chief reason for this want of success is the greater cost of the material consumed as compared with the fuel of other engines. A pound of zinc costs about fifty times as much as a pound of coal, and if the full equivalent in the form of work could be obtained, both for the coal burned in a furnace and for the zinc consumed in a battery, a pound of coal would yield four times as much work as a pound of zinc. Hence, if the "efficiency"[1] of a heat-engine and of an electric engine be the same, the cost of performing a given quantity of work will be 200 times greater for the electric engine than for the other. It appears, however, that, as regards efficiency, the electro-magnetic engine may have an advantage of about 4 to 1. This would make its work only 50 times as expensive as that of a steam-engine.

Again, inasmuch as magnetic attractions decrease very rapidly with increase of distance, it is necessary for efficient working that the travel of the driving parts should be very small. This is inconvenient from a mechanical point of view.

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[1] That is to say, the ratio of the energy utilized to the whole energy expended. This is the "efficiency of an engine" in the broadest sense. The "efficiency" of Chap. xxxii. is sometimes called, by way of distinction, the "efficiency of the working fluid."

Lastly, as we shall see in a later chapter, the movement of conductors in a strong magnetic field causes induced currents which strongly oppose the motion.

We shall proceed to describe two of the most successful electromagnetic engines which have yet been constructed.

580. Bourbouze's Engine.—In the engine of M. Bourbouze (Fig. 514) the armatures have a reciprocating motion. There are two helices, having soft-iron cores in their interior for the lower half of their length. Two soft-iron rods or plungers travel up and down in the space above the cores, and are jointed to a beam which, by means of a connecting-rod and crank, turns a fly-wheel. The positive pole of a battery is permanently connected with a sliding piece of metal which travels to and fro horizontally, so as to be connected with a terminal of the left-hand or of the right-hand coil, according as it is on the left or the right of its middle position. The upper terminals of both coils are permanently connected with the negative pole of the battery. The reciprocating movement of the slider is produced by an eccentric on the axis of the fly-wheel, like the movement of the slide-valve in a steam-engine.

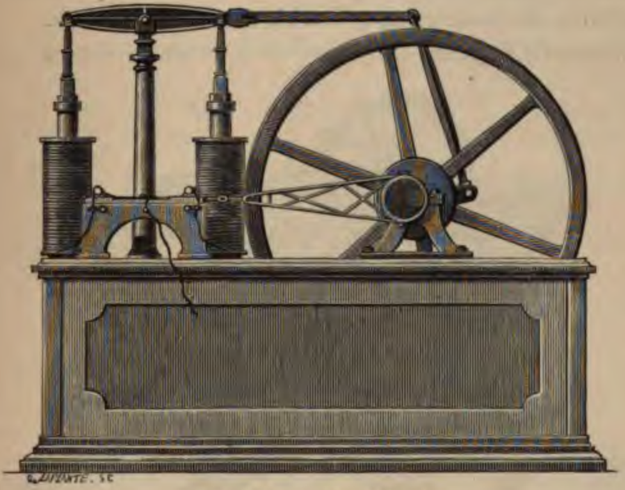

Fig. 514.—Bourbouze's Engine.

In the position represented in the figure, the eccentric and slider are nearly at the extremity of their range to the left. The left plunger is then at the middle of its down-stroke. When it reaches the bottom, the sliding-piece will be in the centre of its travel, and the left-hand coil will just have been disconnected. Immediately afterwards, the right-hand coil will be brought into circuit, its plunger being at the summit of its path; and it will continue in circuit till the plunger is nearly at the bottom. The electro-magnets are thus made and unmade whenever the eccentric passes its highest and lowest positions. On account of the shortness of the stroke, the beam is prolonged to a considerable distance before attaching to it the connecting-rod which drives the crank.

581. Froment's Engine.—Froment's is a rotatory engine. It may be described as consisting of a wheel, with eight armatures of soft iron attached to its circumference at intervals of 45°, rotating under the action of four electro-magnets fixed to a cast-iron frame at intervals of 60°. Each magnet is "made" when an armature comes within 15° or 20° of it, and "unmade" as the armature is passing it.

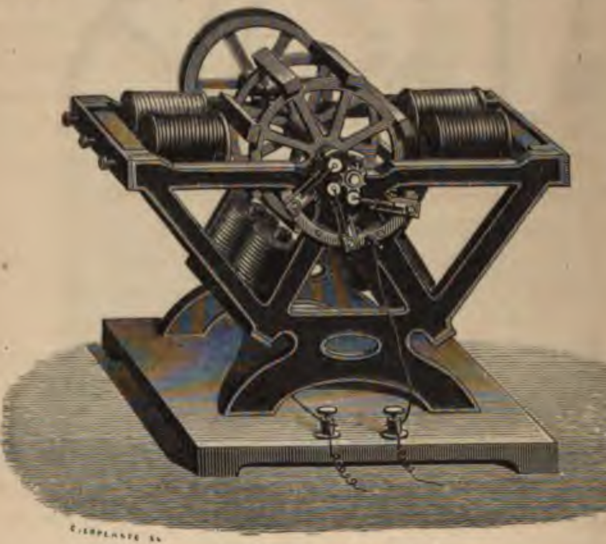

Fig. 515.—Froment's Engine.

The making and breaking of the circuits is effected by means of three distributors, one of which is shown on an enlarged scale in Fig. 516. R is an eight-toothed wheel, fixed to the axis on which the armatures revolve, and turning with them. Each tooth, as it passes the roller r, pushes it away, and brings the studs m' m into contact. As long as they remain in contact, the current circulates through the coil with which the distributor is connected. The distributors are screwed into a metallic arc, which is constantly connected with one pole of the battery. One of them serves for the two opposite horizontal magnets, which are made and unmade together. The two lower magnets have one distributor apiece. Matters are so arranged that the current is not cut off from one coil till just after it has commenced to flow in the next. This precaution prevents, or at least mitigates, the induction-spark which (for reasons to be hereafter explained) generally occurs in breaking circuit, and which has the mischievous effect of oxidizing the contacts, and thus, after a time, deranging the movements.

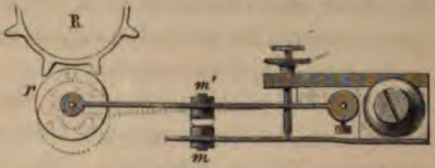

Fig. 516.—Distributor.

582. Electric Telegraph: History.—The discovery that electricity could be transmitted instantaneously to great distances, at once suggested the idea of employing it for signalling. Bishop Watson, already referred to in § 466, performed several experiments of this kind in the neighbourhood of London, the most remarkable being the transmission of the discharge of a Leyden-jar through 10,600 feet of wire suspended between wooden poles at Shooter's Hill. This was in 1747. A plan for an alphabetical telegraph to be worked by electricity is minutely described in the *Scot's Magazine* for 1753, but appears to have been never experimentally realized. Lesage, in 1774, erected at Geneva a telegraph line, consisting of twenty-four wires connected with the same number of pith-ball electroscopes, each representing a letter. Reusser, in Germany, proposed, in the same year, to replace the electroscopes by spangled panes exhibiting the letters themselves. The difficulty of managing frictional electricity was, however, sufficient to prevent these and other schemes founded on its employment from yielding any useful results. Volta's discoveries, by supplying electricity of a kind more easily retained on the conducting wires, afforded much greater facilities for transmitting signals to a distance.

Several suggestions were made for receiving-apparatus to exhibit the effects of the currents transmitted from a voltaic battery. Sömmering of Munich in 1811 proposed a telegraph, in which the signals were given by the decomposition of water in thirty-five vessels, each connected with a separate telegraph wire. Ampère, in 1820, proposed to utilize Œrsted's discovery, by employing twenty-four needles, to be deflected by currents sent through the same number of wires; and Baron Schilling exhibited in Russia, in 1832, a telegraphic model in which the signals appear to have been given by the deflections of a single needle.[1]

Weber and Gauss carried out this plan in 1833, by leading two wires from the observatory of Göttingen to the Physical Cabinet, a distance of about 9000 feet. The signals consisted in small deflections of a bar-magnet, suspended horizontally with a mirror attached, on the plan since adopted in Thomson's mirror galvanometer.

At their request the subject was earnestly taken up by Professor Steinheil of Munich, whose inventions contributed more perhaps than those of any other single individual to render electric telegraphs commercially practicable. He was the first to ascertain that earth-connections might be made to supersede the use of a return wire. He also invented a convenient telegraphic alphabet, in which, as in most of the codes since employed, the different letters of the alphabet are represented by different combinations of two elementary signals. Two needles were employed, one or the other of which was deflected according as a positive or a negative current was sent, the deflections being always to the same side. Sometimes the needles were merely observed by eye, sometimes they were made to strike two bells, and sometimes to produce dots, by means of capillary tubes charged with ink, on an advancing strip of paper, thus leaving a permanent record on the strip in the shape of two rows of dots. His currents were magneto-electric, like those of Weber and Gauss.

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[1] The contributions of Mr. (now Sir Francis) Ronalds to the art of telegraphy must not be altogether overlooked. According to an able notice in *Nature*, Nov. 23, 1871, "Sir Francis, before 1823, sent intelligible messages through more than eight miles of wire insulated and suspended in the air. His elementary signal was the divergence of the pith-balls of a Canton's electrometer produced by the communication of a statical charge to the wire. He used synchronous rotation of lettered dials at each end of the line, and charged the wire at the sending end whenever the letter to be indicated passed an opening provided in a cover; the electrometer at the far end then diverged, and thus informed the receiver of the message which letter was designated by the sender. The dials never stopped, and any slight want of synchronism was corrected by moving the cover. Hughes' printing instrument is the fully-developed form of this rudimentary instrument. A gas pistol was used to draw attention, just as now a bell is rung. The primary idea of reverse currents is to be found where Sir Francis suggests that the wire when charged with positive electricity should discharge not to earth but into a battery negatively charged. Equally interesting is the discussion on what we now call lateral induction, then known as compensation. The author clearly saw that in the underground wires which he suggests as substitutes for aerial lines, this induction would be or might be a cause of retardation."

The attraction of an electro-magnet on a movable armature furnishes another means of signalling. This was the foundation of Morse's telegraphic system, and was employed by Wheatstone for ringing a bell to call attention before transmitting a message.

About the year 1837 electric telegraphs were first established as commercial speculations in three different countries. Steinheil's system was carried out at Munich, Morse's in America, and Wheatstone and Cooke's in England. The first telegraphs ever constructed for commercial use were laid down by Wheatstone and Cooke, on the London and Birmingham and Great Western Railways. The wires, which were buried in the earth, were five in number, each acting on a separate needle; but the expensiveness of this plan soon led to its being given up. The single-needle and double-needle telegraphs of the same inventors have been much more extensively used, the former requiring only one wire, and the latter two.

Wheatstone (now Sir Charles Wheatstone) has since contributed several important inventions to the art of telegraphy, some of which we shall have occasion to mention in later sections.

583. Batteries.—All the public telegraphs in this country have now for many years been worked by voltaic currents; the magneto-electric system, which was tried on some lines, having been found to involve a needless expenditure of labour.

According to Mr. Culley,[1] engineer-in-chief to the post-office, the battery which has been adopted by the authorities of that department is a modified Daniell's, consisting of a teak trough, divided into cells by plates of glass or slate, and well coated with marine glue, each cell being divided into two by a slab of porous porcelain. The zinc plates measure 4 inches × 2, and the copper plates, which are very thin, are 4 inches square. The zinc hangs at the upper part of its cell, which is filled with dilute solution of sulphate of zinc. The copper cell is filled with a saturated solution of sulphate of copper, and crystals of this salt are placed at the bottom. The expenditure in sulphate of copper is about a pound and a half for each cell per annum.

584. Wires.—The wires for land telegraphs are commonly of what is called galvanized iron, that is, iron coated with zinc, supported on posts by means of glass or porcelain insulators, so contrived that some part of the porcelain surface is sheltered from rain, and insulates the wires from the posts even in wet weather. Wires thus suspended are called *air-lines.*

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[1] *Handbook of Practical Telegraphy*, edition 1871, p. 19.

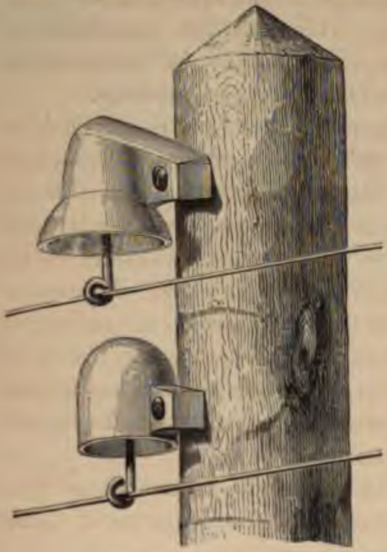

Fig. 517.—Insulators.

Underground wires are, however, sometimes employed. They are insulated by a coating of gutta-percha, and are usually laid in pipes, an arrangement which admits of their being repaired or renewed without opening the ground except at the drawing-in boxes. There is less leakage of electricity from subterranean than from air lines, but their cost is greater, and they are less suited for rapid signalling, on account of the retardation caused by the inductive action between the wire and the conducting earth, which is similar to that between the two coatings of a Leyden jar.

The early inventors of electric telegraphs supposed that a current could not be sent from one station to another without a return wire to complete the circuit. Steinheil, while conducting experiments on a railway, with the view of ascertaining whether the rails could be employed as lines of telegraph, made the discovery that the earth would serve instead of a return wire, and with the advantage of diminished resistance; the earth, in fact, behaving like a return wire of infinitely great cross-section, and therefore of no resistance.

We are not, however, to suppose that the current really returns from the receiving to the transmitting station through the earth. The duty actually performed by the earth consists in draining off the opposite electricities which would otherwise accumulate in the terminals. It keeps the two terminals at the same potential; and as long as this condition is fulfilled, the current will have the same strength as if the terminals were in actual contact.

584 A. Single-needle Telegraph.—One of the best known telegraphs in this country, though little or not at all employed elsewhere, is the single-needle instrument of Wheatstone and Cooke, represented in Figs. 517 A, B, the former showing its external appearance, and the latter its internal arrangements as seen from behind. The needle, which is visible in front, is one of an astatic pair, its fellow being in the centre of the coil CC. When the handle H hangs straight down, the instrument is in the position for receiving signals from another station. The current from the line-wire enters at L, and, after traversing the coil and deflecting the needle, escapes through the earth-wire E, having taken in its course the two tall contact-springs *t′ t*.

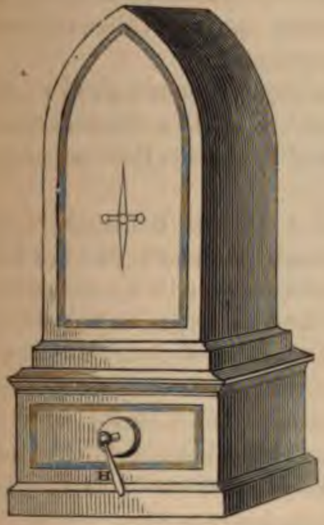

Fig. 517 A.—Single-needle Instrument.

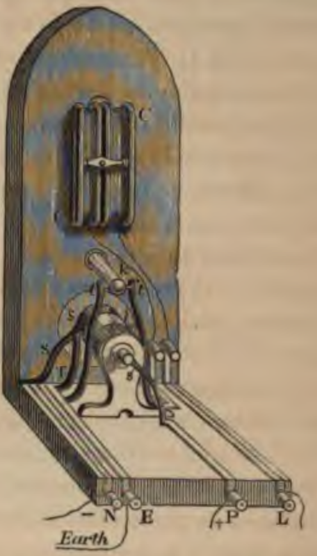

Fig. 517 B.—Internal Arrangements.

To send a current to another station, the handle H is moved to one side, and the current sent will be positive or negative according to the side to which the handle is moved. The handle turns the cylindrical arbor *a b*, which is divided electrically into two parts by an insulator in the middle of its length. Each of these parts has a pin projecting from it, one pin being above, and the other below. These are vertical when the handle is vertical, and are then doing no duty; but when the handle is put to one side, the upper pin (which is attached to *b*) makes contact with one of the tall springs *t t′*, at the same time pushing it away from the metallic rest *k*, and thus putting it out of connection with the other tall spring; while the lower pin (which is attached to *a*) makes contact with one of two short springs

T T′, only one of which is shown in the figure. There is permanent connection between *a* and the negative pole of the battery through the spring *s*, and between *b* and the positive pole through the spring *s*′. In the position represented in the figure, *a* serves to connect the negative pole of the battery with the earth, and *b* serves to connect the positive pole with the spring *t*′, down which the current passes from the point of contact of the pin, and then through the coil to the line-wire at L. The needle of the sending station is thus deflected to the same side as that of the receiving station.

If the handle were moved to the other side, *b* would serve to connect the positive pole with the earth, and *a* would establish connection between the negative pole and the coil, which is itself connected with the line-wire.

Since the telegraphs of this country came into the hands of the post-office, the alphabet devised by Wheatstone and Cooke has been given up, and the Morse alphabet, which we give in a later section, adopted in its place. In the Morse alphabet, which is now the telegraphic alphabet of all nations, the shortest signs are allotted to those letters which occur most frequently. This was not the case with the old needle-alphabet, which was rather planned with the view of assisting the memory; and experience has shown that such assistance is quite unnecessary. The needle instrument is also, to a great extent, being superseded by Morse's instrument.

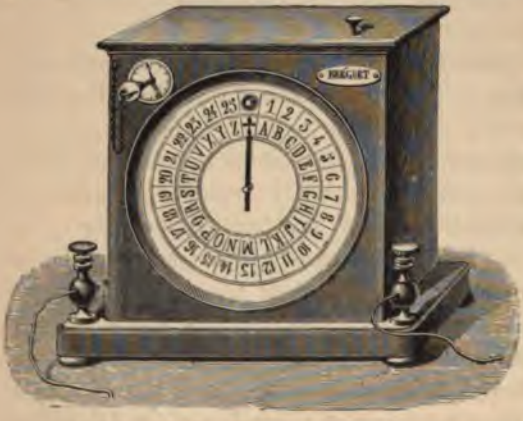

Fig. 518.—Breguet's Indicator.

585. Dial Telegraphs.—Telegraphs in which the ordinary letters of the alphabet are ranged round the circumference of a dial, and are pointed at by a revolving hand, are specially convenient for those who are not professional telegraphists. They are constructed on the principle of step-by-step motion, the hand being advanced by successive steps, each representing one current sent or stopped.

One of the simplest instruments of this class is Breguet's, which is extensively used on the French railways. Fig. 518 represents the exterior of the receiving instrument. The dial is inscribed with the 25 letters of the French alphabet and a cross, making 26 signals in all. The hand (as in other step-by-step telegraphs) advances only in one direction, which is the same as that of the hands of a clock, stopping before each letter which is to be indicated, and pointing to the cross at the end of each word. Fig. 519 shows the mechanism by which the motion is produced. A is the armature of an electro-magnet, the magnet itself being removed in the figure, to allow the other parts to be better seen. The two dotted circles traced on the armature represent vertical sections of the two coils, which rest on the bottom of the box, and have their axes horizontal. If introduced, they would nearly conceal the armature from view. The armature turns about a horizontal axis V V′, and is attached to an opposing spring which draws it back from the magnet. The tension of this spring can be regulated by means of a lever acted on by a key outside the box. When a current is sent, the armature is attracted to the magnet; when the current ceases, the spring draws it back; and it thus moves continually to and fro during the transmission of a message. An upright arm *l* is attached to the armature, and carries a horizontal arm *c*, which lies between the two prongs of a fork *d*, represented on a larger scale in Fig. 520. This fork vibrates about a horizontal axis *a b*, to which is attached the vertical pallet *i*. This

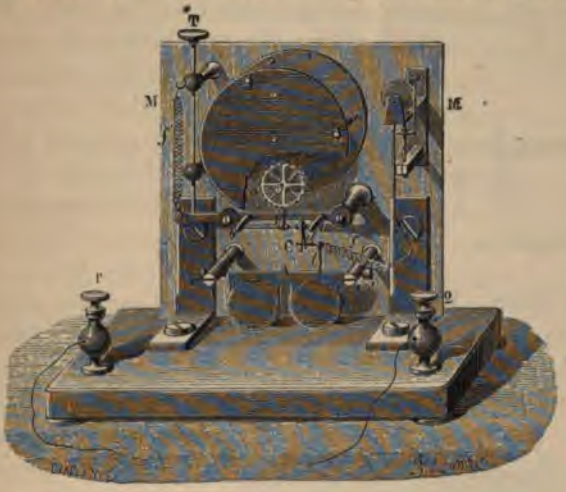

Fig. 519.—Mechanism of Indicator.

pallet acts upon an escapement wheel O, toothed in a peculiar way, the thickness of the teeth being only half the thickness of the wheel, and the teeth on one half of the thickness being opposite the spaces on the other half. The total number of teeth is 26, thirteen on each half of the thickness.

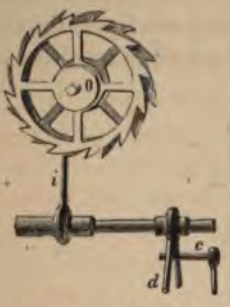

Fig. 520.—Escapement.

When no current is passing, the pallet *i* is engaged with one of the teeth on the remote side, as represented in Fig 520. When a current passes, the armature is attracted, and the pallet is moved over to the near side, thus releasing the tooth with which it was previously engaged, and becoming engaged with the next tooth on the near side of the wheel. The wheel, which is urged by a clock-movement, thus advances $\frac{1}{26}$ of a revolution; and the hand on the dial, being attached to the wheel, moves forward one letter. When the current ceases, the pallet moves back to the remote side, and the hand is advanced another letter. If the hand is initially at the cross, it will be advanced to any required letter by so arranging matters that the number of currents *plus* the number of interruptions shall be equal to the number denoting the place of the letter in the alphabet. To effect this arrangement is the office of the sending instrument.

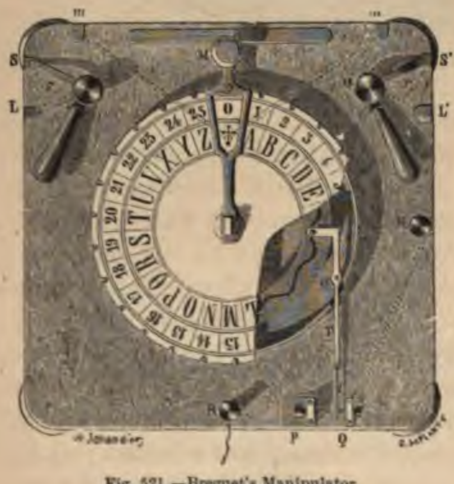

Fig. 521.—Breguet's Manipulator.

586. Sending Instrument.—This is represented in Fig. 521. There is a dial inscribed with 25 letters and a cross, like that of the receiving instrument, and an arm which can be carried round the dial by a handle M. There are 26 notches cut in the edge of the dial, in which a pin attached to the movable arm catches; and the arm is allowed sufficient play to and from the face of the dial to admit of this pin being easily released or inserted. When the pin is in one of the notches, the instrument is in position for transmitting the corresponding letter. The action is as follows:—

A toothed or rather undulated wheel is fixed on the same axis as the revolving arm, and turns with it. There are 13 projections and 13 hollows on its circumference, a few of which are shown in the figure where the face is cut away. A bent lever T, movable about an axis at *a*, bears at one end against the circumference of the undulated wheel, while its other end plays between two points P, Q, and is in contact with one or other of these points whenever its upper end bears against a hollow or a projection. P is in connection with a battery, and Q with the earth, the undulated wheel being in connection with the line-wire. The movement of the handle thus produces the requisite number of currents and interruptions.

587. Alarum.—Besides the sending and receiving apparatus above described, each station has an *alarum*, which is employed to call attention before sending a despatch. There are several different kinds. Fig. 522 represents the *vibrating alarum*, which is one of the simplest. It contains an electro-magnet *e*, with an armature *f* fixed to the end of an elastic plate. When no current is passing through the coil, the armature is held back by the elasticity of this plate, so as to press against a contact-spring *g* connected with the binding-screw *m*. The terminals of the coil are at the binding-screws *p*, *p′*, the former of which is in connection with the armature, and the latter with the earth. As long as the armature presses against the spring *g*, there is communication between the two binding-screws *m* and *p′* through the coil; but the passing of a current produces attraction of the armature, which draws it away from *g* and interrupts the current. The electro-magnet is thus demagnetized, and the armature springs back against *g*, so as to allow a fresh current to pass. The armature is thus kept in continual vibration; and a hammer K, which it carries above, produces repeated strokes on a bell T.

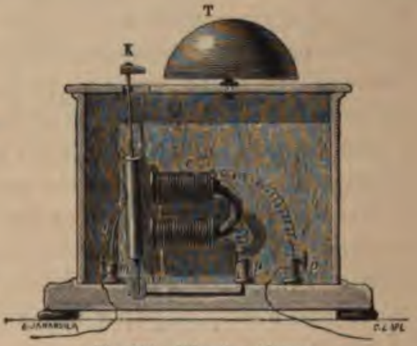

Fig. 522.—Vibrating Alarum.

587A. Wheatstone's Universal Telegraph.—The first step-by-step telegraph was invented by Wheatstone; and the most perfect instrument of the class is probably his "Universal Telegraph," which is now in such general use in this country for connecting places of business. The currents employed are magneto-electric, and are alternately positive and negative. They produce successive reversals of polarity in an electro-magnet, which acts upon a light steel magnet—a kind of astatic needle—and causes it to rotate through a large angle first in one direction, and then in the opposite. Each of these rotations causes a ratchet-wheel to advance one tooth, and this causes the pointer to advance one letter. At the same time, the turning of the handle by which the currents are generated, causes the pointer of the sending instrument to advance one letter for each current sent, so that the pointers at the two stations indicate the same letter. The same dial which serves for sending, also serves for receiving. It is surrounded by a number of keys or buttons, one against each letter. When any letter is to be sent, its key is depressed, the operator continuing all the time to turn the handle for generating currents. Previous to putting down a key, these currents complete their circuit within the instrument; but when a key is down, every current generated travels along the line to the receiving station, until the pointers have been advanced step by step to the corresponding letter. As soon as this has been reached, the currents are again confined to the sending instrument; and the pointers will make no further advance till another key is put down.[1]

588. **Morse's Telegraph.**—Morse's apparatus, first tried in America about 1837, is now perhaps the most extensively used of all.

His receiving instrument, or *indicator*, in its primitive simplicity, consists (Fig. 523) of an electro-magnet, a lever movable about an axis, carrying a soft-iron armature at one end, and a pencil at the other, and a strip of paper which is drawn past the pencil by a pair of rollers.

As the pencil soon became blunt, and was uncertain in its marking, a point, which scratched the paper, was substituted. This has now to a great extent been superseded by an ink-writer, which requires the exertion of less force, and at the same time leaves a more visible trace.

589. **Receiving Instrument.**—Fig. 524 represents Morse's indicator

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[1] For the details of the mechanism, reference may be made to Wheatstone's Patent, No. 1239 year 1858. A condensed account will be found in *Sabine on the Electric Telegraph*, pp. 82-84.

as modified by Digney. A train of clock-work, not shown in the figure, drives one of a pair of rollers *n m*, which draw forward a strip of paper *p p* forming part of a long roll K. The same train turns the printing-cylinder H, the surface of which is kept constantly charged with a thick greasy ink by rolling-contact with the ink-pad L. The

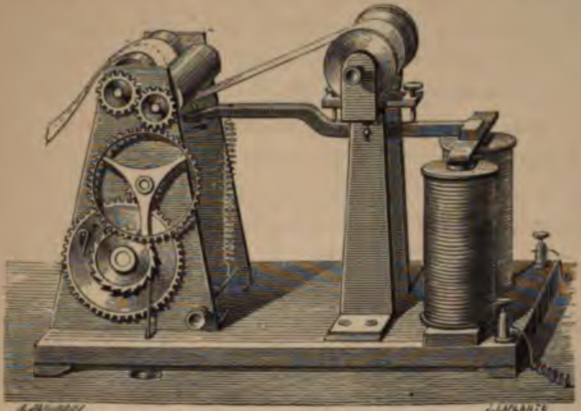


Fig. 523.—Morse's Telegraph.

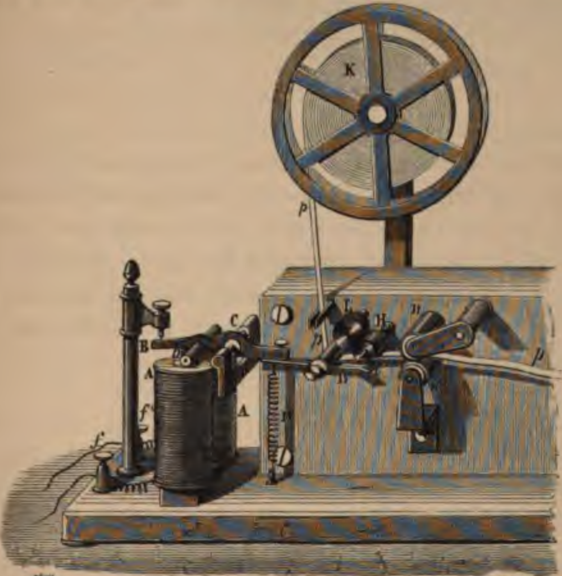


Fig. 524.—Modified Form.

armature B B′ of the electro-magnet A is mounted on an axis at C, and carries a style at its extremity just beneath the printing-cylinder. When a current passes, the armature is attracted, and the style presses the paper against the printing-cylinder, causing a line to be printed on it, the length of which depends on the duration of the current, as the paper continues to advance without interruption. The lines actually employed are of two lengths, one being made as short as possible (-), and called a *dot*, the other being about three times as long (—) and called a *dash*. The opposing spring D restores the armature to its original position the moment the current ceases.

590. Key for Transmitting.—Morse's key (Fig. 525) is simply a brass lever, mounted on a hinge at A, and pressed up by the spring *f*. When the operator puts down the key, by pressing on the button K with his finger, the projections *c d* are brought into contact, and a current passes from the battery-wire P to the line-wire L. When the key is up, the projections *a b* are in contact, and currents arriving by the line-wire pass by the wire R to the indicator or the relay. By keeping the key down for a longer or shorter time, a dash or a dot is produced at the station to which the signal is sent. The dash and dot are combined in different ways to indicate the different letters, as shown in the following scheme, which is now generally adopted both in Europe and America:—

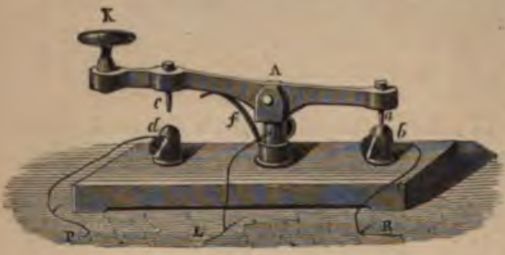


Fig. 525.—Morse's Key.

MORSE'S ALPHABET.

A ·—
Ä ·—·—
B —···
C —·—·
D —··
E ·
É ··—··
F ··—·
G ——·
H ····
I ··

J ·———
K —·—
L ·—··
M ——
N —·
O ———
Ö ———·
P ·——·
Q ——·—
R ·—·
S ···

T —
U ··—
Ü ··——
V ···—
W ·——
X —··—
Y —·——
Z ——··
Ch ————
Understood ···—·

1 ·————
2 ··———
3 ···——
4 ····—
5 ·····
6 —····
7 ——···
8 ———··
9 ————·
0 —————

A space about equal to the length of a dash is left between two letters, and a space of about twice this length between two words.

In needle-telegraphs, the dot is represented by a deflection to the left, and the dash by a deflection to the right.

Fig. 526 represents Morse's indicator in connection with what is called a *relay;* that is to say, an apparatus which, on receiving a feeble current from a distance, sends on a much stronger current from a battery on the spot. The key B being up, a current arriving by the line-wire passes through the key from *c* to *a*, thence through another wire to the coil of the electro-magnet belonging to the relay, and through this coil to earth. The electro-magnet of the relay attracts an armature, the contact of which with the magnet completes the circuit of the local battery, in which circuit the coil belonging to the indicator is included. The armature of the indicator is thus compelled to follow the movements of the armature of the relay.

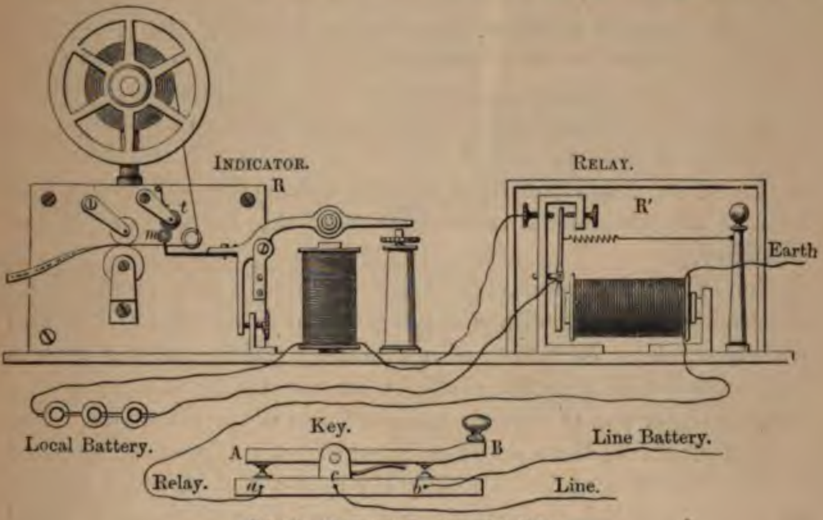


Fig. 526.—Morse's Apparatus, with Relay

Relays are used when the currents which arrive are too much enfeebled to give clear indications by direct action. They are also frequently introduced at intermediate points in long lines which could not otherwise be worked through from end to end. The analogy of this use to change of horses on a long journey is the origin of the name. Relays are also frequently used in connection with alarums when these are large and powerful.

591. Hughes' Printing Telegraph.—The employment of Morse's alphabet requires on the average about three currents to be sent per letter. The extension of telegraphic service has stimulated the industry of inventors to devise means for obtaining more rapid transmission. Hughes, about 1859, invented a system which requires only one current to be sent for each letter, and which, accordingly, sends messages in about a third of the time required by Morse's method. Hughes' machine also prints its messages in Roman characters on a strip of paper. These advantages are, however, obtained at the expense of extreme complexity in the apparatus employed. It is only fit for the use of skilled hands; but it is extensively employed on important lines of telegraph. We will proceed to indicate the fundamental arrangements of this marvellous piece of ingenuity.

Fig. 527 is a general view of the machine. It is propelled by powerful clock-work, with a driving-weight of about 120 lbs., and with a regulator consisting of a vibrating spring l acting upon a 'scape-wheel. A travelling weight on the spring can be moved towards either end to regulate the quickness of the vibrations. The clock-work drives three shafts or axes: (1.) the type-shaft, so called because it carries at its extremity the type-wheel T, which has the letters of the alphabet engraved in relief on its circumference at equal distances, except that a blank space occurs at one place instead of a letter; (2.) the printing-shaft, which turns much faster than the type-shaft, making sometimes 700 revolutions per minute, and carrying the fly-wheel V. These two axes are horizontal, and are separately represented in Fig. 528; (3.) a vertical shaft a, having the same velocity as the type-wheel, which drives it by means of bevel-wheels.

This vertical shaft consists of two metallic portions, insulated from each other by an ivory connecting-piece. In the position represented in Fig. 528, these two metallic parts are electrically connected by means of the screw V, but they will be disconnected by raising the movable piece v.

The revolving arm composed of the pieces $v'v$ is called the *chariot.* It revolves with the vertical shaft, and travels over a disc D pierced with as many holes as there are letters on the type-wheel, these holes being ranged in a circle round the base of the shaft, and at such a distance from the shaft that the extremity of the chariot passes exactly over them. In these holes are the upper ends of a set of pistons, which are raised by putting down a set of keys BN resem-

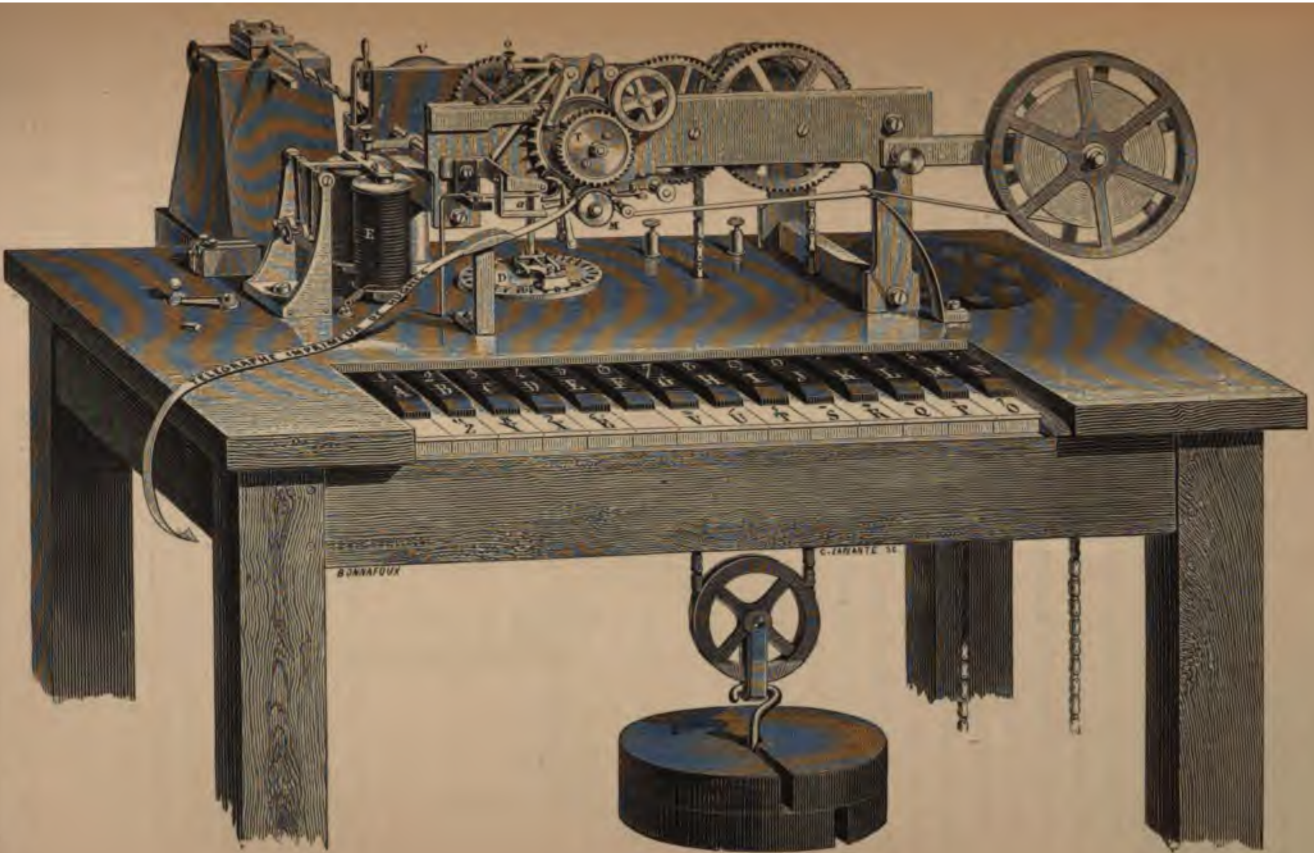


Fig. 527.—Hughes' Printing Telegraph.

bling those of a piano. When the chariot passes over a pin which is thus raised, the piece *v* is lifted away from *v′*, and the current from the battery, which previously passed from the pin through *v* and *v′* to the earth, is now cut off from *v′*, and passes through *v* to the electro-magnet, and thence to the line-wire.

This is the process for sending signals. We will now explain how a current thus sent causes a letter to be printed by the type-wheels at both the sending and receiving stations, the sending and receiving instruments being precisely alike.

The current traverses the coils of an electro-magnet E (Fig. 527), beneath which is a permanent steel horse-shoe magnet, having its poles in contact with the soft-iron cores of the electro-magnet. When no current is passing, the influence of the steel renders these cores temporary magnets, and enables them to hold the movable armature *p* against the force of an opposing spring. The current is in such a direction that it tends to reverse the magnetism induced by the steel. It is not necessary, however, that it should be strong enough to produce an actual reversal, but merely that it should weaken the induced magnetism of the cores sufficiently to enable the

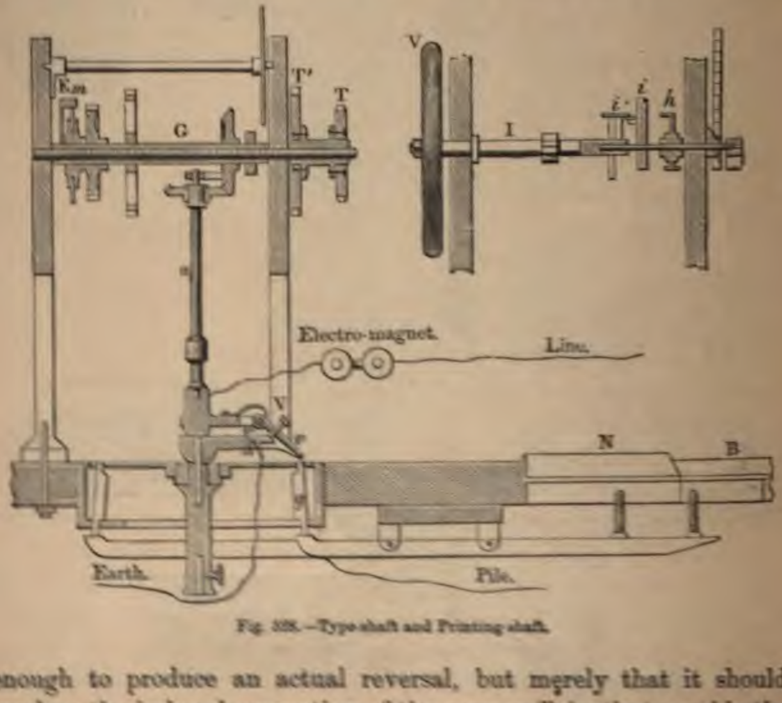


Fig. 528.—Type-shaft and Printing-shaft.

opposing spring to overpower them. This is one of the most original parts of Hughes' apparatus, and is a main cause of its extreme sensibility.

The printing-shaft consists of two portions, one of which I (Fig. 528) carries the fly-wheel V, and turns uniformly under the action of the clock movement; the other, which is next the front of the machine, remains at rest when no current is passing; but when the armature of the magnet rises, the two parts of the shaft become locked together by means of the ratchet-wheel and click *i i'*.

The portion of the shaft which is thus turned every time a current passes, carries a very acute cam or tooth *p* (Fig. 529), which suddenly raises the lever *a b*, movable about an axis at one end T, and, by so doing, raises the paper against the type-wheel, and prints the letter. In order thus to print a letter from the rim of a wheel which continues turning, very rapid movement is necessary. This is secured by making the opposing spring which moves the armature very powerful, and the cam *p* very acute. The same movement of the lever which produces the impression, raises the arm J U, which carries a spring *r* with a click at its extremity. This click, in its ascent, glides over the teeth of the ratchet-wheel E; but locks into the teeth and turns the wheel in its descent, and by so doing, advances the paper through the distance corresponding to one letter. The spacing of the words is obtained by the help of the blank on the type-wheel.

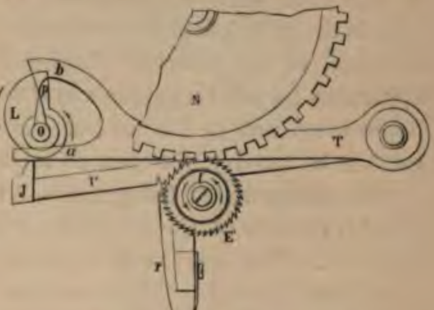


Fig. 529.—Mechanism for Printing.

The type-wheel should admit of easy adjustment to restore it to agreement with the chariot when accidental derangement may have occurred. For this purpose, the shaft G is made hollow, its internal and external portions being merely locked together by the click *m*, which is held in its place by a permanent current in either direction. On pressing down the button Q (Fig. 527), the click *m* is raised by the piece E, so as to leave the type-wheel free, and a pin is provided which catches in a notch corresponding to the blank on the type-wheel. The adjustment can also be made by hand.

Lastly, the shaft I carries a third cam, which, at each revolution of this axis, engages with a very coarse-toothed wheel T', set on the same axis as the type-wheel, and pushes it a little forward or backward without detaching it from the driving gear. Small discrepancies between the velocities of the type-wheel and chariot are thus corrected as often as a letter is printed. This contrivance serves to keep the receiving instrument from gaining or losing on the sending instrument during the transmission of a message. The type-wheel of the receiving instrument must be adjusted before the message begins, so as to make the two instruments start at the same letter.

592. Electro-chemical Telegraph.—Suppose a metallic cylinder, permanently connected with the earth, to be revolving, carrying with it on its surface a strip of paper freshly impregnated with cyanide of potassium. Also suppose a very light steel point permanently connected with the line-wire, and resting in contact with the paper. Every time that a current arrives by the line-wire, chemical action will take place at the point of contact, and the paper at this point will be discoloured by the formation of prussian blue. This is the principle of Bain's electro-chemical telegraph, which leaves a record in the shape of dots and dashes of prussian blue. The apparatus for sending signals is the same as in Morse's system. The paper must not be too wet, or the record will be blurred; neither must it be too dry, for then no record will be obtained.

593. Autographic Telegraph.—An autographic telegraph is one which produces at the receiving station a fac-simile of the original despatch. The best known instruments of this class are those of Bonelli and Caselli. We shall describe the latter.

At the sending station a sheet of metallized paper, with the [illegible] written upon it in a greasy kind of ink, is laid upon a [illegible] M (Fig. 530). At the receiving station there is a

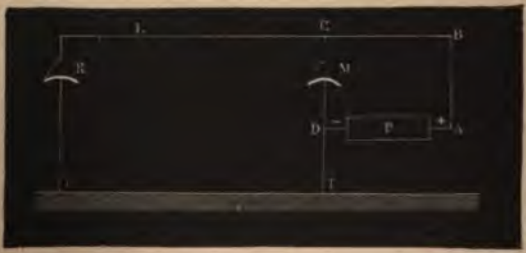


Fig. 530.—Principle of Caselli's Telegraph.

imilar cylindric surface R, on which a sheet of Bain's chemical paper s laid. Two styles, driven by pendulums which oscillate with exact synchronism, move over the surfaces of the two sheets, describing upon them very close parallel lines at a uniform distance apart, both

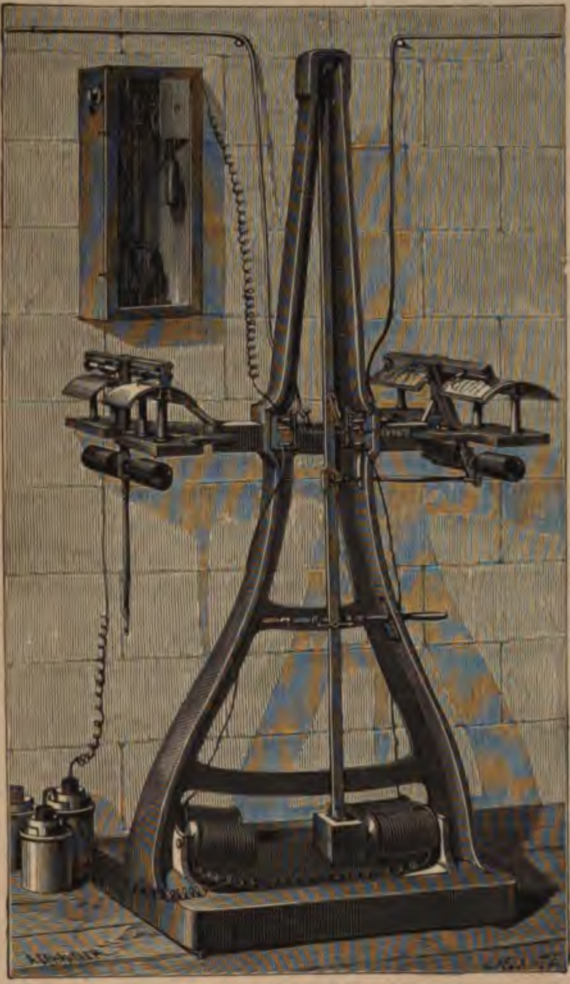


Fig. 531.—Caselli's Telegraph.

styles being in permanent connection with the line-wire. The current is furnished by the battery P at the sending station. When the style is on a conducting portion of the paper M, the current takes the course of least resistance A B C D, no sensible portion of it going to the other station. On the other hand, when the style is on the non-conducting ink in which the despatch is written, the circuit ABCD is broken, and the current travels through the line-wire. At this moment the style on the sheet R is in exactly the same position as that on the sheet M, by reason of the synchronism of the pendulums, and a blue line will be produced which will be the exact reproduction of the broken line of the despatch traversed by the style. Accordingly, when the style of M has described a series of lines close together and covering the sheet, R will be covered with a series of points or lines forming a copy of the despatch. The tracing point is carried by a lever turning about an axis near its lower end. To this lower end is attached a connecting-rod, jointed at its other end to the pendulum (Fig. 531). While the pendulum swings in one direction, the style traces a line in one direction on the sheet. At the end of this stroke, an action occurs which, besides advancing the style, raises it, so that it does not touch the sheet during the return stroke.

The synchronism of the pendulums at the two stations, which is absolutely necessary for correct working, is obtained by means of two clocks which are separately regulated to a given rate, the clock-pendulums making two vibrations for one of the telegraphic pendulum. The bob of the latter consists of a mass of iron, and vibrates between two electro-magnets, which are made and unmade according to the position of the clock-pendulum, as the latter makes and breaks the circuit of a local battery. The mass of iron is thus alternately attracted by each of the two magnets as it comes near them, and is prevented from gaining or losing on the clock.

It is evident that the Caselli telegraph may be applied to copy not only letters but a design of any kind; hence the name of *pantelegraph* which has been given it. Fig. 532 represents a copy thus obtained upon Bain's paper. Fig. 533 represents a copy obtained at the same time upon a sheet of tin-foil, such as is usually placed beneath the paper. The current decomposes the moisture of the paper, and the hydrogen thus liberated reduces the oxide of tin, of which a small quantity is always present on the surface. If the foil be then treated with a mixture of nitric and pyrogallic acid, the traces are developed, and come out black.

The Caselli system has been used for some years on the telegraphs around Havre and Lyons, but has not realized the hopes of its promoters, its despatches being often illegible.

Instead of a series of parallel lines, the styles may be made to trace the successive convolutions of a fine helix, the two sheets being bent round two cylinders, which revolve in equal times, and also advance longitudinally.

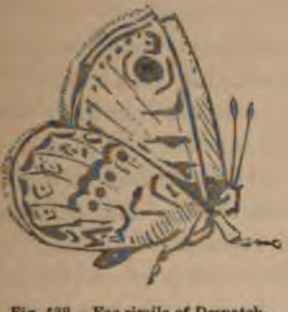


Fig. 532.—Fac-simile of Despatch.

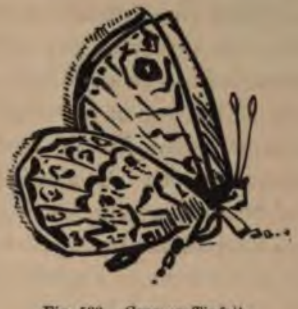


Fig. 533.—Copy on Tinfoil.

595. Submarine Telegraphs.—The first submarine telegraph cable was laid between Dover and Calais in 1850; but, being insufficiently protected against the friction of the rocks, it only lasted a few hours. The two Atlantic cables which were laid in 1866 appear to be still in perfect order.

Submarine cables are now usually constructed by imbedding a certain number of straight copper wires in gutta-percha (Fig. 534), which insulates them from each other; this is surrounded with tarred hemp, and several strands of iron wire are wound outside of all. The copper wires in the interior are the conductors for the transmission of the signals; the gutta-percha is for insulation; the hemp and iron are for protection.

The Atlantic cables contain a central conductor, consisting of seven copper wires, twisted together and covered with three layers of gutta-percha, forming altogether a cylinder $\frac{3}{8}$ of an inch in diameter. This is covered with a layer consisting of five strands of hemp, served with a composition consisting of 5 parts of Stockholm tar, 5 of pitch, 1 of linseed-oil, and 1 of bees'-wax. Lastly, the whole is covered by 18 strands of charcoal iron, each strand consisting of seven wires $\frac{7}{10}$ of a millimetre in diameter. On leaving the

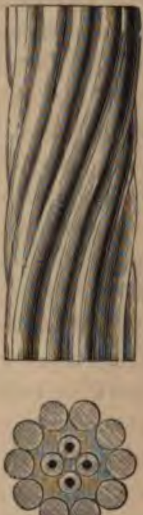


Fig. 534. Submarine Cable.

machine which put on the wire covering, the cable was passed through a cauldron contain a mixture of pitch, tar, and linseed-oil. The difficulty of obtaining sufficiently good insulation has thus been completely surmounted.

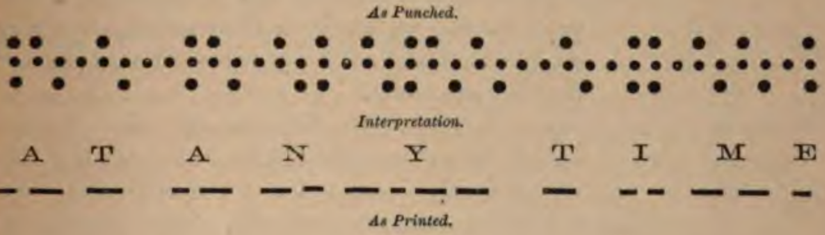
A second difficulty attaching to submarine telegraphy depends upon the inductive action of the surrounding water, or of the iron sheath. This action, which is found quite sensible in subterranean lines of no great length, becomes of immense importance in long submarine cables. The cable forms one enormous condenser, the central conductor representing the inner coating, and the sea-water, or iron sheath, the outer coating of a Leyden jar. In the Atlantic cables, the retardation of the signals due to this cause is so considerable that it would be barely possible to obtain a speed one-fifth of that usually attained on land-lines, if the same modes of sending and receiving signals were employed. The electrical capacity of the cable is in fact so enormous, that a long time is required to give it a full charge from a battery, or to discharge it again. The signals accordingly lose all their sharpness, and run into one another, unless special precautions are taken. After sending a current from one pole of the battery, the cable must be discharged, either by putting it to earth, or, still better, by connecting it for an instant with the other pole of the battery. The residual effects of the first current are thus quickly destroyed, and the line is left free for a second signal.

As the first effect received through such a cable is very slight, a very sensitive receiving instrument is necessary for quick working. Thomson's mirror galvanometer (§ 536A) is the instrument which has been hitherto employed, the signals being read off by an attendant who watches the movements of the spot of light, dots and dashes being represented by deflections in opposite directions. A self-recording instrument by the same inventor is now coming into use, in which the signals are written with ink discharged from a very light glass siphon, the siphon being moved by a very light coil of fine copper wire, suspended by a silk fibre between the poles of a very powerful permanent magnet. The coil turns in one direction or the other according as the current transmitted is positive or negative, thus producing opposite sinuosities in the ink record which is traced upon an advancing strip of paper. The regular flow of the ink is assisted by electrical attraction, on the principle of the bucket or watering-pot described in § 445; but with this difference, that it is not the ink but the paper that is electrified. An electrical machine of peculiar and novel construction, bearing some resemblance to the replenisher of § 469 E, is employed for this purpose.

595 A. Wheatstone's Automatic System.—Another very effective contrivance for increasing the speed of signalling, is Wheatstone's automatic apparatus, which is being very extensively adopted by the authorities of the postal telegraphs. The first step towards sending a message by this system consists in punching the message in a ribbon of stiff paper. The punching is done by a special instrument, the operator having merely to put down three keys, one of which represents *dot*, another *dash*, and the third *blank*. The holes punched are in three rows. Those in the middle row are equidistant, and are intended to perform the office of the teeth of a rack in guiding the paper uniformly forwards. Those in the two outside rows contain the message, a dot being represented by a pair of holes exactly opposite each other (:) one in each row, and a dash by two holes ranged obliquely (˙.).

The punched strips are then put through the transmitting instrument, and, by regulating the movements of two pins, cause the transmission of the currents necessary for printing the message at the receiving station. From 60 to 100 words are thus transmitted per minute and automatically printed.

The following is a specimen of three consecutive words of a telegraphic message, as it appears on the punched strip at the sending station, and on the printed strip at the receiving station:—



The speed thus attained is three or four times greater than that of ordinary writing. The practical limit to speed, in lines of considerable length, arises not so much from the difficulty of making quicker movements, as from the blending together of successive signals in travelling a great distance, especially if part of the distance be under ground or under water. This evil is partly remedied by making each signal consist, not of a single current, but of two; thus a dot will be produced by an instantaneous current, *immediately* succeeded by another of opposite sign; a dash by an equally short current followed *at a longer interval* by an opposite one. In this way, though a greater number of currents are required for each word, a greater number of words can be distinctly signalled in a given time; and, by sending three properly adjusted currents for each signal, a still greater speed of distinct transmission is possible. The transmitting instrument of Wheatstone's automatic system does in fact send three currents for each dot or dash.

595 B. Electrically-controlled Clocks.—Various schemes have been proposed for utilizing electricity in connection with the driving and government of clocks. In some of them, electricity is employed either to wind up the driving-weight, or to fulfil the office of a driving-weight by its own action, a pendulum being employed as the regulator, as in ordinary clocks. In others, electricity both drives and regulates the clock (or even a considerable number of clocks), by means of currents which keep time with the movements of a standard clock, electricity having thus to do the work both of driving and regulating the dependent clocks.

But the system which has given the best practical results is that of Mr. R. L. Jones, in which the dependent clocks are complete clocks, able to go of themselves, and keep moderately good time, without the aid of electricity. The duty devolving on the electric currents is merely to supply the small amount of accelerating or retarding action necessary to prevent the dependent clocks from gaining or losing on the standard clock by whose movements the currents are timed.

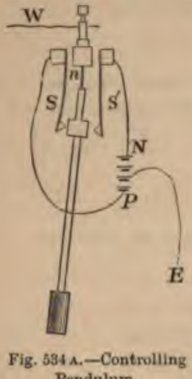


Fig. 534 A.—Controlling Pendulum.

The arrangements for attaining this end are shown in the annexed figures 534 A, 534 B, which represent the pendulums of the controlling and controlled clocks respectively. These pendulums are supposed to be almost precisely of the same length, so that they would nearly synchronize if disconnected.

The controlling pendulum, in its movement to either side, comes in contact with one or the other of two weak springs SS', which are connected with the poles of a battery PN, having one of its middle plates connected with the earth, so as to keep its poles at potentials differing from that of the earth in opposite directions. In the position represented in the figure, a current is being sent from the positive pole P into the wire W. When the pendulum swings over to the other side, a negative current will be sent.

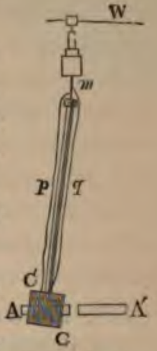


Fig. 534 B.—Controlled Pendulum.

The bob C C of the controlled pendulum (Fig. 534 B) is a hollow cylinder of soft iron encircled by a coil, whose ends are connected through two suspending springs at *m* with the wire W and the earth respectively. The consequence of this arrangement is that, whenever a current arrives by the wire W, the bob becomes an electro-magnet.

Two steel magnets A A′ are fixed, with their poles turned opposite ways, in such a position that the hollow bob of the pendulum always encircles one or both of them. Suppose, in the figure, that the poles A A′ which are turned outwards, are the two austral poles, so that the two boreal poles are facing each other. Then matters are to be so arranged that, in the position represented, the pendulum being near the left extremity of its swing, the right-hand end of the coil is a boreal pole, and magnetic force urges the pendulum to the left. When the pendulum is near the right extremity of its swing, the current is in the opposite direction, and consequently the boreal pole of the coil is its left-hand end. The pendulum will thus experience magnetic force urging it to the right. If the pendulum tends to gain upon the standard, its return from the extremities of its swing is thus opposed for a longer time than its outward movement is aided; and if it tends to lose, the assistance to its motion lasts longer than the opposition. Its tendency to deviate from the standard clock either way is thus checked, and the correcting action is greater as the deviation from coincidence is greater. The controlling power thus obtained is so great, that even if the electrical connections are interrupted during several consecutive beats, the accumulated errors will be completely wiped off after the connections are restored.

CHAPTER LI.

ELECTRO-CHEMISTRY

596. Electrolysis.—When a current is passed through a compound liquid, decomposition is frequently observed, two of the component substances being separated, one at the place where the current enters, and the other at the place where it leaves the liquid. This decomposition is called *electrolysis,* and the substance decomposed or *electrolyzed* is called the *electrolyte.* The action only occurs in the case of liquids, and these must be conductors.

The process may be illustrated by the decomposition of water in

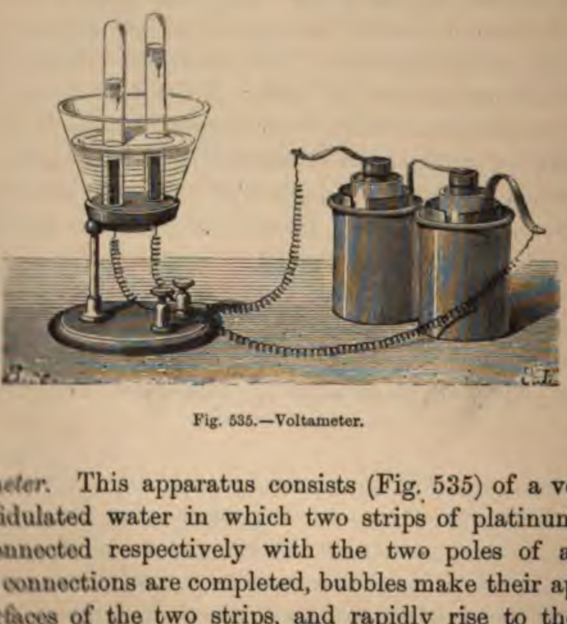


Fig. 535.—Voltameter.

the *voltameter.* This apparatus consists (Fig. 535) of a vessel containing acidulated water in which two strips of platinum are immersed, connected respectively with the two poles of a battery. When the connections are completed, bubbles make their appearance at the surfaces of the two strips, and rapidly rise to the surface.

These are bubbles of oxygen and hydrogen respectively, the former being evolved at the positive, and the latter at the negative strip. To complete the voltameter, inverted tubes must be provided for collecting the gases as the bubbles rise to the surface and burst. It will be found that the volume of the hydrogen is about double that of the oxygen. The presence of a little acid in the water serves to improve its conductivity, and according to the theories of Faraday and his contemporaries answers no other purpose. Pure water conducts so badly that its electrolysis is extremely difficult. The two platinum strips in the above arrangement are called the *poles* or electrodes of the voltameter. They may obviously be regarded as the poles of the battery. The direction of the current through the liquid is of course from the positive to the negative pole. The element which comes to the positive pole (oxygen) is called electro-negative, and that which comes to the negative pole (hydrogen) electro-positive, these names being based on the idea of attraction between electricities of opposite sign.

597. Transport of Elements.—The positive element may be defined as that which travels with the current, and the negative element as that which travels against it. Hence Faraday calls the former the *cation* (signifying *that which goes down*), and the latter the *anion* (signifying *that which goes up*), and instead of applying the name *poles* to the places where the current enters and leaves the liquid, he calls them the *anode* and *cathode*. The direction of the current through the liquid is from the anode to the cathode, the former being what is commonly called the positive pole, and the latter the negative pole. When speaking of them jointly, he calls them the *electrodes.*

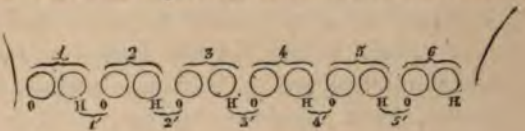


Fig. 536.—Grotthus' Hypothesis.

It is a remarkable fact that the separated elements never make their appearance except at the electrodes. Nothing is seen of them, nor is any action exhibited, at intermediate points. The appearance is as if the gases could vanish from one extremity and appear at the other without passing through the intermediate space. The only possible explanation of this phenomenon seems to be what is known as Grotthus' hypothesis, that all the particles of the water in the course of the current undergo continual decomposition and recomposition. Thus if Fig. 536 represent a line of particles traversed by the current from left to right, there will be a continual stream of hydrogen-particles along this line from left to right, and a stream of oxygen[1] particles from right to left. The hydrogen of molecule 1 will combine with the oxygen of molecule 2 to form a new molecule 1′; the hydrogen of molecule 2 will combine with the oxygen of molecule 3 to form a new molecule 2′, and so on. The oxygen of molecule 1 is given off at the left-hand extremity, which we suppose to be the point of contact with one of the strips of platinum, and the hydrogen of molecule 6 at the other strip. The molecules 1′, 2′, 3′ . . . are then in their turn decomposed to form a new set. In actual cases, the number of molecules, instead of being only 6 as represented in the figure, is of course many millions.

598. Electrolysis of Binary Compounds.—When a compound formed by the union of a metal with some other elementary substance is submitted to electrolysis, the metal always comes to the negative pole. It was in this way that several of the metals were first obtained from their oxides by Sir Humphrey Davy. Potassium, for example, was obtained by placing a piece of potash on a platinum disk connected with the negative pole of a battery of 250 cells, and then applying a platinum wire connected with the positive pole to its upper surface. The potash, which had been allowed to contract a little moisture from the atmosphere, in order to give it sufficient conducting power, soon began to fuse at the points of contact of the electrodes. A violent effervescence occurred at the upper or positive electrode; while at the lower surface small globules appeared resembling quicksilver, some of which instantly burst into flame, while others merely became tarnished and afterwards coated over with a white film.

The earthy oxides, such as magnesia and alumina, are more difficult of reduction than the alkalies potash and soda, and have never yet been electrolyzed. The metals magnesium and aluminium have, however, been obtained by the electrolysis of their chlorides. Chloride of magnesium, for example, is melted by heating it to redness in a porcelain crucible, the upper part of which is divided into two compartments by a porous partition. Pieces of carbon are employed as the terminals of the battery, and are inserted one in each of these compartments, the piece which is to serve as the negative electrode being notched like the edge of a saw, with its teeth pointing downwards ready to intercept the metal in its upward course—the metal being specifically lighter than its chloride. It was by the electric current that Deville in 1854 succeeded in preparing aluminium, which has exhibited such unexpected and interesting properties.

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[1] According to modern theories, the anion is not oxygen, as here stated, but a compound of oxygen and sulphur. (See § 600.) The explanation as it stands in the text represents the views held by Faraday and his contemporaries.

For the electrolysis of binary compounds soluble in water, their solutions are frequently employed, but these should in general be highly concentrated.

599. Electrolysis of Salts.—When a salt of any of the less inflammable metals is submitted to electrolysis, a continual deposition of the metal is observed on the negative electrode; while, at the positive electrode, oxygen is disengaged, and acid set free. These effects occur, for example, if platinum electrodes are plunged in a solution of sulphate of copper. If an oxydizable metal is employed as the positive electrode, the oxygen will combine with it instead of being given off. If the metal employed be copper itself, the oxide of copper formed will combine with the acid, and a quantity of sulphate of copper will be formed exactly equal to that which undergoes decomposition. The solution thus remains constantly in the same state as regards saturation, and the copper deposited on the negative electrode is exactly compensated by that dissolved off the positive electrode.

When a salt of one of the alkaline metals is electrolyzed, the appearances presented are different from those which we have just been describing; and they for a long time received an erroneous interpretation. Let the tube represented in Fig. 537 be charged with solution of sulphate of soda coloured with syrup of violets. If the current be then passed, after the lapse of some time, a red tinge will be observed in the liquid around the positive electrode, and a green tinge around the negative. This shows the presence of free acid at the positive and alkali at the negative pole. Oxygen is also found to be evolved at the positive and hydrogen at the negative pole. The interpretation for a long time given to these results was, that, in the electrolysis of a salt, the acid went to the positive and the base to the negative pole. In the case of a metallic salt, such as

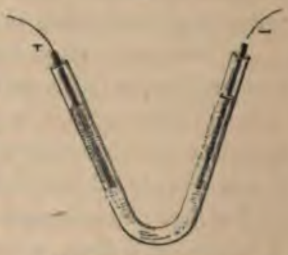

Fig. 537.—Decomposition of Salts.

sulphate of copper, it was supposed that the oxide of copper which forms the base, underwent a further electrolysis, resulting in the appearance of the metal at the negative and of the oxygen at the positive pole. This complicated hypothesis of two successive electrolyses is entirely gratuitous. It was in fact simply framed to suit the chemical theories which regarded a salt as the result of the union of an acid and a base. It is now believed that the electrolysis of sulphate of soda is single, that it consists in resolving the salt into sodium and an unstable compound of sulphur and oxygen, SO_4, to which the name of sulphion has been given. The sodium unites with the oxygen of the water at the negative pole, thus forming soda and liberating hydrogen; and the sulphion unites with the hydrogen of the water at the positive pole, forming sulphuric acid and liberating oxygen. These chemical actions immediately consequent upon electrolysis are called *secondary actions.*

600. Electrolysis of Water.—What we have just said of salts, applies equally to the oxygen acids. Thus in the electrolysis of sulphuric acid (SO_3, H_2O) the hydrogen, which is a kind of gaseous metal, goes to the negative pole, while the substance SO_4 goes to the positive pole, and there unites with the hydrogen of the water to form the primitive compound, setting oxygen free.

It is probable that what is called the electrolysis of water is really an indirect action of this kind; that, in fact, it is not the water, but the acid contained in it that is electrolyzed, decomposition and recomposition of acid being in continual progress.

Be this as it may, voltameters are frequently employed for the measurement of currents, from which use indeed they derive their name. This mode of measuring a current is due to Faraday. The quantity of electricity which passes is measured by the quantity of gas evolved; and this is best determined by measuring the hydrogen, in the first place because of its greater volume, but still more because it is less liable than oxygen to be absorbed by water. It is important that the temperature at which the operation is conducted should not be too low; for if it be under 20° C., the water may become so strongly impregnated with oxygen as to be able to take up some of the hydrogen which is separated at the negative pole, and reduce it again to the form of water.

Voltameters have the disadvantage, as compared with galvanometers, of introducing opposing electro-motive force into the circuit, as well as a large amount of resistance.

601. Definite Laws of Electrolysis.—The following principles were completely established by Faraday's researches:—

1. The quantity (*i.e.* mass) of a given electrolyte decomposed by a current is simply proportional to the quantity of electricity which passes through it,—in other words, is jointly proportional to the strength of the current and the time that it lasts; or, the rate of decomposition of a given electrolyte is simply proportional to the strength of current, and is independent of all other circumstances.

2. The quantities (masses) of different electrolytes decomposed by the same quantity of electricity are directly as their chemical equivalents.[1]

These laws can be extended to the cells of the battery themselves, if we pay proper attention to the signs of the quantities involved. The essential difference between a cell of the battery and a decomposing cell included in the circuit is, that the former contributes positive, and the latter negative electro-motive force to the circuit; and if one of the cells of the battery be reversed, so that the current travels through it not from zinc to copper as usual, but from copper to zinc, it immediately becomes a decomposing cell with electro-motive force opposing that of the circuit. The amount of chemical combination that takes place in a battery cell (or the excess of combination over decomposition, if both are going on, as in a Daniell's cell, where sulphate of copper is decomposed) is chemically equivalent to the decomposition that occurs in any one decomposing cell in the same circuit. This is on the supposition that no local action (§ 521) is allowed to take place in the battery. Keeping Grotthus' hypothesis in view, we may therefore assert that the total chemical action is the same in amount for all sections of the current, whether these sections are taken in battery cells or in decomposing cells; but is opposite in sign, according as the sections are made across cells which assist, or which oppose the current by their electro-motive force.

If a current generated by a battery consisting of several cells arranged in a series, is passed through a succession of decomposing cells, one containing acidulated water, another chloride of lead, another protochloride of tin in a state of fusion, and another a concentrated solution of nitrate of silver, then for 65 parts by weight of zinc dissolved in any one cell of the battery, 2 parts of hydrogen will be evolved from the acidulated water, and 207 parts of lead, 118 of tin, and 216 of silver, from the other electrolytes respectively; these numbers being proportional to the chemical equivalents of zinc, hydrogen, lead, tin, and silver.

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[1] This law applies directly, and without exception, to the decompositions effected by the direct action of the current. It is not always (though usually) applicable to the final results of electrolysis, when secondary actions come into play. In certain cases, for example, the final result will be exactly double what the law would give.

If several cells containing the same electrolyte are placed in different parts of the circuit, so as to be traversed in succession by the same current, the same amount of decomposition will be effected in them all; and this amount for each cell will be the full equivalent of the action in each cell of the battery.

In order to effect a given amount of decomposition in a given cell, with the smallest possible consumption of zinc in the battery, the number of battery cells employed should be the smallest that will suffice to effect the operation at all; in other words, the resultant electro-motive force in circuit should barely exceed zero. This is obvious from considering that the quantity of electricity required to effect the given operation is irrespective of the number of cells of the battery, and is absolutely constant. The quantity of zinc dissolved *in each cell* is therefore constant also, and hence the whole zinc dissolved is proportional to the number of cells. If we employ more cells than are necessary, we shall effect the required operation more quickly, but at the expense of an extra consumption of zinc.

Time may be saved by increasing the number both of the decomposing cells and of the battery cells. By doubling them both, we shall double the electro-motive force and also the resistance, so that the current will be unaltered. The chemical action in each cell will therefore be the same as before; and as the number of decomposing cells is doubled, a double quantity of the given electrolyte is decomposed.

602. Polarization of Electrodes.—When electrodes have been doing duty for some time in the decomposition of an electrolyte, if we detach them from the battery, plunge them in a conducting liquid, and connect them externally by a wire, we shall find that a current is circulating in the opposite direction to the original current.

Suppose, for example, that the Bunsen battery M (Fig. 538) has been employed for electrolyzing sulphate of potash by means of the electrodes A B, A being the positive, and B the negative electrode, the current flows through the decomposing cell from A to B. Now let the battery be removed, and the electrodes connected externally by the wire N. A current will now pass through the liquid *from B to A*, completing its circuit through the wire.

The origin of this current can be explained in the following way. During the process of decomposition, potash collects on the electrode B, and sulphuric acid on the electrode A. When the connecting wire is substituted for the battery, the two substances which have been forced to separate begin to unite again; and as their tendency to do so produced an opposing electro-motive force while the direct current was passing, this tendency is now manifested in the actual production of a reverse current and reverse transport of elements. It is not necessary that the deposition of the two substances on the plates should have been brought about by electrolysis. A similar result will be obtained if the plates be coated with the two substances in any other way

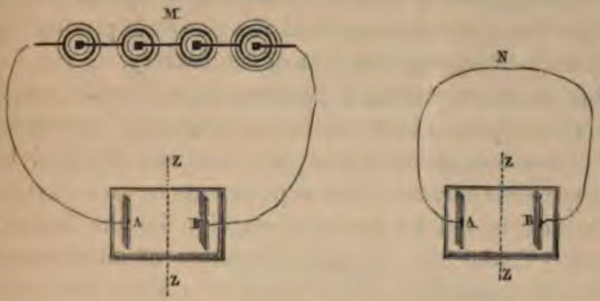

Fig. 538.—Polarization of Electrodes.

Grove's *gas-battery* is constructed by immersing two platinum plates in a vessel of acidulated water, the upper halves of the plates being surrounded, one by oxygen, and the other by hydrogen, inclosed in inverted tubes. External communication must be made between the plates by means of wires sealed into the upper ends of the tubes, and a current will pass through the circuit thus completed; or, if there are more cells than one, the hydrogen plate of each cell must be connected with the oxygen plate of the next, and the first and last plates must also be connected. In each cell, union of the two gases will gradually take place through the acidulated water, and the direction of the current will be opposite to that which would restore the gases to their places if the cell were used as a voltameter; that is to say, it will be through the liquid from the plate in hydrogen to the plate in oxygen. The plates employed for this purpose are usually covered with a deposit of finely-divided platinum, as the great extent of surface thus obtained conduces to rapid action.

Ritter's *secondary pile* consists of a number of discs all of the same metal separated by pieces of moistened cloth. If its two extremities be connected for a few seconds with the poles of a battery, the pile will be found to have acquired the power of producing, for a short time, a current opposite to that of the battery.

603. Feeble Currents through Electrolytes.—Liquids capable of undergoing electrolysis never conduct electricity without being electrolyzed. Some exceptions were at one time supposed to exist in cases of very feeble currents; but experiments in vacuo have shown that these are explained by the re-absorption by the liquid of the gases evolved. Under the exhausted receiver of an air-pump the gases are actually given off. There appears to be no real exception to the rule that electricity, in traversing an electrolyzable liquid, always produces its full equivalent of decomposition.

604. Electro-metallurgy.—The applications of electrolysis to the arts are numerous and important. They are of two kinds. In one, the electrolytic deposit is intended as a permanent covering, and should adhere perfectly so as to form one mass with the body which it covers. In the other, the adhesion is temporary, and must not be too close, the object being merely to obtain an exact copy of the original form. Electro-plating belongs to the former class; electrotype to the latter.

605. Electro-gilding and Electro-plating.—The deposition of a coating of gold or silver on the surface of a less precious metal is merely an example of the electrolysis of a salt, as described in § 599. The metal in solution is always deposited on the negative electrode; hence we have merely to make the negative electrode consist of the article which we wish to coat. The only points to be decided practically relate to the means of making the deposit solid and firmly adherent. These ends have been completely attained by the methods patented about 1840 by Elkington in England and Ruolz in France.

The solutions are always alkaline, and usually consist of the cyanide or chloride of the metal, dissolved in an alkaline cyanide.

To prepare the *gold-bath*, 50 grammes of fine gold are dissolved in aqua regia; and the solution is evaporated till it has the consistence of syrup. Water is then added, together with 50 grammes of cyanide of potassium, and the mixture is boiled. The quantities named give about 50 litres of solution.

The negative electrode consists of the article to be gilded. The positive electrode is a plate of fine gold, which constitutes a soluble electrode, and serves to keep the solution at a constant strength. In order that the gilding may be well done, the bath must be maintained, during the operation, at a temperature of from 60° to 70° Centigrade.

Fig. 539 represents a form of apparatus which is very frequently employed. The poles of the battery are connected with two metallic rods resting on the top of the cistern which contains the bath. The articles to be gilded are hung from the negative rod. From the positive rod is hung a plate of gold, whose size should be proportional to the total surface of the articles which form the negative electrode.

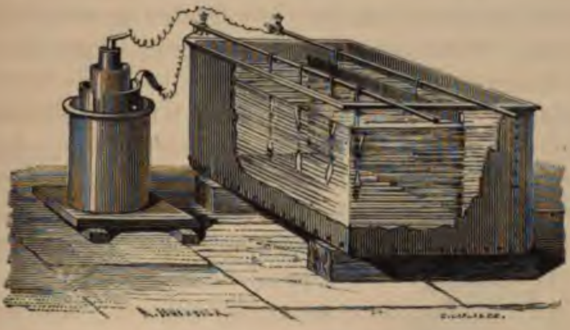

Fig. 539.—Apparatus for Electro-gilding.

The *silver bath* is a solution containing 2 parts of cyanide of silver, 10 of cyanide of potassium, and 250 of water. The operation of plating is the same as that of gilding, except that the apparatus is usually on a larger scale, and that the temperature may be lower.

In both cases the surfaces to be coated must be thoroughly cleansed from grease. For this purpose they are subjected to the processes of pickling and dipping, which we cannot stay to describe.

Other bodies, as well as metals, can be coated, if their surfaces are first covered with some conducting material. Baskets, fruits, leaves, &c., have thus been gilded or silvered.

Similar processes are employed for depositing other metals, of which copper is the most frequent example.

606. Electrotype.—Electrotyping consists in obtaining copper casts or fac-similes of medals, engraved plates, &c., by means of electrolytic deposition. The first successful attempts in this direction were made about 1839 by Jacobi at St. Petersburg and Spencer in England. The art is now very extensively practised.

If a fac-simile of a medal is required, a cast is first taken of it, either in fusible alloy, plaster of Paris, or gutta-percha softened by heating to 100° C., this last material being the most frequently employed. The fusible alloy is a conductor; the other materials are not, and their surfaces are therefore rendered conducting by rubbing them over with plumbago. The mould thus prepared is made to serve as the negative electrode in a bath of sulphate of copper, a copper plate being used as the positive electrode. When the current passes, copper is deposited on the surface of the mould, forming a thin sheet, which, when detached, is a fac-simile of one side of the original medal. A similar process can be applied to the other side, and thus a complete copy can be obtained.

In operations of this kind, the bath itself is often made to serve as the battery. Fig. 540 represents such an arrangement.

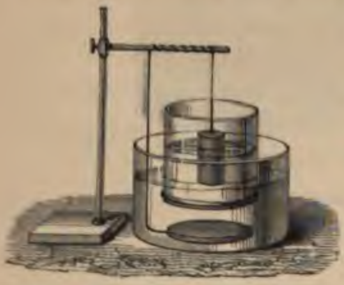

Fig. 540.—Bath and Battery in one.

In the interior of a vessel containing a saturated solution of sulphate of copper, a second vessel is supported, consisting either of porous earthenware or of a glass cylinder closed below by a membrane. In this second vessel is placed acidulated water, with a cylinder of zinc suspended in it. The mould is placed in the outer vessel under the bottom of the porous cylinder, and is connected with the zinc by a stout wire which completes the circuit. The arrangement is evidently equivalent to a Daniell's cell. The current passes through the liquids from the zinc to the mould, electrolyzing the solution of sulphate of copper; and as the metal travels with the current, it is deposited on the surface of the mould. The strength of the solution is kept up by suspending in it crystals of sulphate of copper contained in a vessel pierced with holes.

607. Applications of Electrotype.—One of the commonest applications of electrotype is to the production of copies of wood engravings. The original blocks, as they leave the hand of the engraver, could not yield a large number of impressions without being materially injured by wear. When many impressions are required, they are not taken directly from the wood, but from an electrotype taken in copper from a gutta-percha mould. The process of deposition is continued only for twenty-four hours, and the plate of copper thus obtained is very thin. It is strengthened by filling up its back with melted type-metal. Such plates will afford about 80,000 impressions, and it is from them that nearly all the illustrations in popular works are printed. Postage stamps, which must be exactly alike in order to prevent counterfeits, are also printed from electrotypes; and, on account of the great number of impressions required, the electrotypes themselves need frequent renewal; but the operations necessary for this purpose do not sensibly injure the original.

Copperplate engravings and even daguerreotypes can be very accurately reproduced in copper. No preparation of the surface is necessary, as the thin film of oxide which is present is quite sufficient to prevent the deposit from adhering too closely.

Gasaliers are usually of cast-iron coated with copper by electrolysis. The copper is not, however, deposited on the surface of the iron, as the contact of the two metals would greatly promote the oxidation of the iron, if any of it were accidentally exposed to the air. The iron is first painted over with red-lead, which, when dry, is covered with a very thin layer of plumbago to render it conducting; and it is on this that the copper is deposited.

CHAPTER LII.

INDUCTION OF CURRENTS.

608. Induced Currents.—Induced currents may be described as currents produced in conductors by the influence of neighbouring currents or magnets. Their discovery by Faraday in 1831 constitutes an epoch in the history of electrical science. We shall first describe some modes of producing them; and then state their general laws.

609. Currents induced by Commencement and Cessation of Currents.—Let two coils be wound upon the same frame B, one of them, called the secondary coil, having its ends connected with the binding-screws of the galvanometer G, while the ends of the other, which is called the primary coil, dip in two cups of mercury *g g′* connected with the two plates of the voltaic element P. As long as the current is passing steadily in the primary coil, the needle of the galvanometer remains undeflected; but if the current be stopped, by lifting a wire out of one of the mercury cups, the needle is immediately deflected, indicating the existence of a current in the same direction as that which

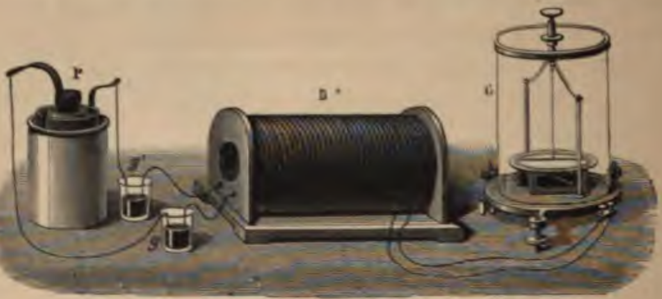

Fig. 541.—Current induced by Commencement or Cessation.

was previously circulating in the primary coil. This effect is very transitory. The needle appears to receive a sudden impulse which immediately passes away. If the current be then re-established, there is a deviation to the other side, indicating a current in the opposite direction to that in the primary coil; and this deviation, like that which occurred before, is merely the effect of an instantaneous impulse, the needle making a few oscillations from side to side, and then remaining steadily at zero. This experiment, which is substantially the same as that by which Faraday first made the discovery, establishes the following proposition:—*When a current begins to flow, it induces an inverse current in a neighbouring conductor; when it ceases, it induces a direct current; and both the currents thus induced are merely instantaneous.*

610. Currents induced by Variations of Strength of Primary Current.—Employing the same apparatus, let us, while the primary current is passing, connect the two mercury cups by the wire *d* (Fig. 542), thus dividing the circuit (§ 547), and causing a great diminution of the current in the primary coil. At the instant of making this connection, the needle of the galvanometer is affected, moving in the same direction as if the primary current were stopped; and on lifting the connecting wire out of one of the cups, so as to produce a sudden increase in the current in the primary coil, the needle moves in the opposite direction. *When a current receives a sudden increase, this produces an inverse current in a neighbouring conductor; and when it is suddenly decreased, a direct current is induced.*

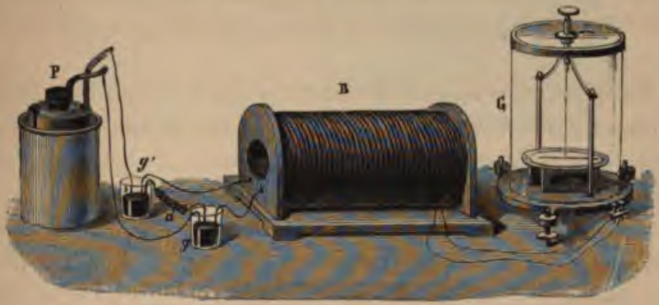

Fig. 542.—Current induced by Change of Strength.

611. Currents induced by Variations of Distance.—Currents may also be induced by change of distance between the primary and secondary conductors. Let the secondary coil, for example, be hollow, as in Fig. 543, and let the primary coil, with the current passing in it, be suddenly introduced into its interior. The galvanometer will indicate the production of an inverse current in the secondary coil.

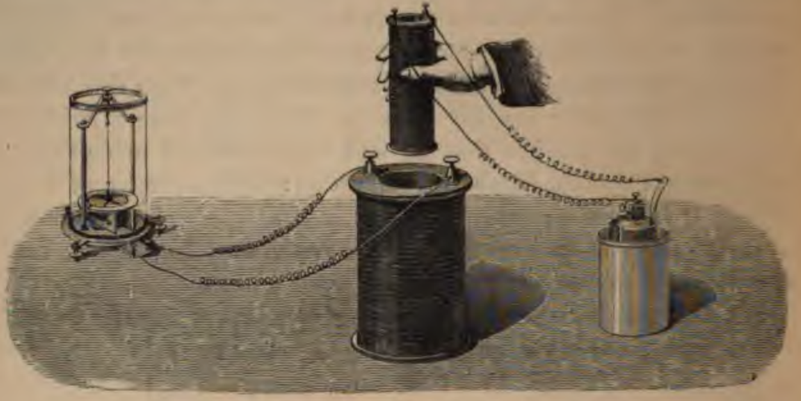

Fig. 543.—Current induced by Change of Distance.

When the needle has come to rest, let the primary coil be withdrawn, and a direct current will be indicated by the galvanometer. These currents differ from those previously mentioned in being less sudden. They last as long as the relative motion of the two coils continues. *When a conductor conveying a current approaches or is approached by a neighbouring conductor, an inverse current is induced in the latter; and when one of these conductors moves away from the other, a direct current is induced.*

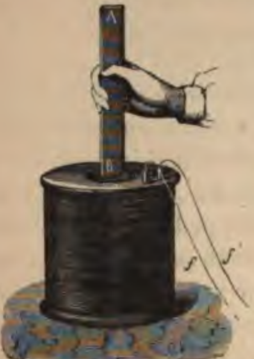

Fig. 544.—Current induced by Motion of Magnet.

612. Magneto-electric Induction.— As a current may be regarded as a magnet (§ 531 A), and a magnet may be regarded as a system of currents (§ 565), induction can be effected by a magnet as well as by a coil.

Let a hollow coil be connected with a galvanometer, and a magnet held over it, as in Fig. 544. As long as the magnet remains stationary, no current is indicated; but when one pole of the magnet is thrust into the interior of the coil, the needle is deflected by an impulse which lasts only as long as the motion of the magnet. If the magnet is allowed to remain at rest in this position, the needle, as soon as it has time to recover from its oscillations, stands at zero; but on withdrawing the magnet, another current will be indicated in the opposite direction to the former.

Currents may also be induced, with even more striking effect, by moving one pole of a magnet towards or from one end of a soft-iron bar previously placed in the interior of the coil (Fig. 545). These currents are due to the magnetism produced and destroyed in the soft iron. *When the intensity of magnetization of a piece of iron or steel undergoes changes, currents are induced in neighbouring conductors.* The directions of these currents can be inferred from the preceding rules by supposing a solenoid to be substituted for the magnet.

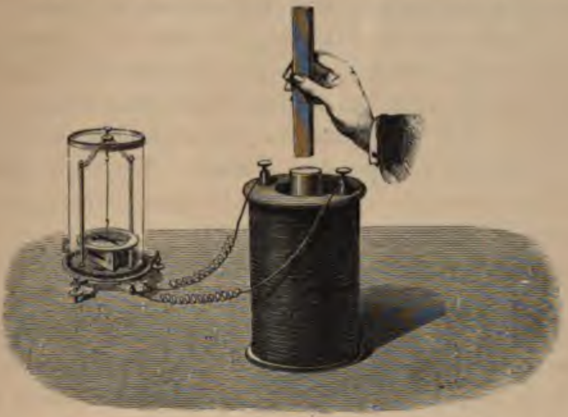

Fig. 545.—Current induced by Magnetization of Soft Iron.

613. Lenz's Law.—*The currents induced by the relative movement either of two circuits or of a circuit and a magnet are always in such directions as to produce mechanical forces tending to oppose the movement.* For example, when two parallel wires, through one of which a current is passing, are made to approach, an opposite current is induced in the other; and opposite currents by their mutual repulsion resist approach. This general law as to the direction of induced currents was first distinctly enunciated by Lenz, a Russian philosopher.

613 A. Direction of Induced Currents specified by Reference to Lines of Magnetic Force.—We have already mentioned, in connection with the mutual forces between magnets and currents (§ 531 B), that a wire conveying a current experiences force perpendicular to its length, and at the same time perpendicular to the lines of magnetic force, when placed in a magnetic field. We have seen that, if the current is from foot to head, and the lines of force (for an austral pole) run from front to back, the force experienced by the wire is a force to the right. Motion of the wire to the right will diminish this force by diminishing the current, motion to the left will increase it by increasing the current, and the amount of increase or diminution is quite independent of the original amount of current. Let the direction of the lines of magnetic force for an austral pole be called *from front to back;* then the motion of a conductor *to the right* generates a current in it *from head to foot,* and motion in the opposite direction generates an opposite current. We shall have frequent occasion to recur to this criterion of direction, which applies to every case of induced currents.

As the generation of currents by induction depends not on absolute but on relative motion, namely the relative motion of the conductor and the lines of magnetic force, the criterion of direction will take the following form when the conductor is supposed to be stationary, and the lines of force to move.[1] Let the direction of the lines of magnetic force for an austral pole be called *from front to back,* then *if the lines of force move so as to cut through the conductor from right to left, a current will be induced in the conductor from head to foot.*

If the conductor forms part of a closed circuit, we shall have a continuous current flowing through it as long as the motion lasts. If the circuit is open, there will merely be an incipient current, which, if its direction be from head to foot, will reduce the end of the conductor which we are regarding as its foot to a higher electrical potential than the other, and this difference of potential will be maintained as long as the motion lasts.

613 B. Quantitative Statements.—In order to state the quantitative laws of induced currents in the simplest and most general manner, we must employ the conception of tubes of force as explained in § 445 G (but they will now be tubes not of electrical but of magnetic force), and we must suppose them to be arranged in the equable manner described in § 445 H. That is to say, we must suppose the whole field cut up into tubes of force in such a manner that, if a cross-section (an equipotential surface as regards magnetic potential) be made in any part of the field, the number of tubes per unit of sectional area is equal to the intensity in that part of the field. It is more usual to speak of *number of lines of force* than of *number of tubes*, the convention being that each tube contains one line; but the counting of tubes rather than lines has the advantage of naturally allowing fractional parts to be reckoned, and not suggesting the idea of discontinuity.

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[1] It may be noted that when a bar-magnet is rotated on its axis, it induces no current in a neighbouring wire, inasmuch as its lines of force cut such a wire once positively and once negatively.

The tubes of force due to a magnet are to be regarded as rigidly attached to the magnet, and carried with it in all its movements, whether of translation or rotation. They undergo no change of size or form unless the magnet itself undergoes changes in its magnetization.

These conceptions being premised, the quantitative laws of induced currents can be stated with great simplicity and complete generality.

1. When a conductor is moved in a magnetic field, the ELECTROMOTIVE FORCE generated by the motion is equal to the number of tubes which the conductor cuts through per unit time.

2. If the conductor forms part of a closed circuit, the CURRENT generated in the circuit is the quotient of the number of tubes cut through per unit time, by the resistance of the circuit; and, lastly,

3. The whole QUANTITY of electricity conveyed by the current is the quotient of the number of tubes cut through, by the resistance of the circuit. The quantity of electricity conveyed by a current of brief duration is measured by observing the swing of a galvanometer needle. It is proportional to the greatest deviation of the needle from zero, provided that this deviation is small, and that the duration of the current is less than that of the swing. When experiments on induced currents are made under these conditions, it is found that the deviation of the needle is not sensibly increased by moving the inducing magnet or coil more rapidly, as long as the ground moved over is the same.

The dependence of the quantity of electricity induced upon the number of tubes cut through, was discovered by Faraday, who established it experimentally by moving a loop of wire in various ways in the vicinity of a magnet. The three foregoing laws were all, in fact, substantially established by the series of researches in which these experiments occur.[1]

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[1] *Researches*, vol. iii. series xxviii.

In counting the tubes cut through, it is necessary to attend to the direction of the current due to the cutting of each tube. Those tubes which are so cut as to give currents in one direction round the circuit (when tested by the criterion of § 613 A) must have one sign given them, and those which give currents in the opposite direction must be reckoned as of the opposite sign. It is in every case the algebraic sum that is to be taken; and if a tube is cut once positively and once negatively, it may be left out of the reckoning.

613c. Relation of Induced Current to Work done.—The direction of the force experienced by any straight portion of a circuit conveying a current in a uniform field, is perpendicular at once to its own length and to the lines of force. If L be its length, a its inclination to the lines of force, C the current flowing through it, and I the intensity of the field, the magnitude of the force will be $CIL \sin a$, and the work done in any movement of translation will be the product of this force by that component of the distance moved which lies in the direction of the force. All this may be more concisely expressed by saying that the work done by magnetic force is the product of C by the number of tubes of force which the wire cuts through in its motion, any tubes which are cut in a direction opposed to that of the force which the wire experiences being counted negatively. *When a closed circuit conveying a current is moved in any magnetic field, the work done upon it by magnetic force is the product of the strength of current by the algebraic number of tubes cut through.*

Comparing this law with the first of the three laws given in the preceding section, we see that the work done per unit time is the product of the actual current and the induced electro-motive force. The original current is *increased* or diminished by the motion, according as work is done *against* or by the magnetic forces of the field.

This result can be shown to be in harmony with Joule's law (§ 571), according to which the energy-value of a current, for each unit of time that it lasts, is the product of the current by the electromotive force producing it. For, if C and E denote the actual amounts of current and electro-motive force, and $C_0 E_0$ the values which these elements would have if there were no motion, the energy required from without to produce the motion is, by the law we are now stating, $C(E-E_0)$, and the energy represented by the additional consumption of zinc in the battery is $(C-C_0)E_0$, since, with a given number of cells, the zinc consumed is simply proportional to the current. The sum of these two expressions is $CE - C_0E_0$; which, by Joule's law, represents the increase in current energy.

When there is no current in the circuit except the induced current, work must always be done against the forces of the field to an amount precisely equal to CE, the energy-value of the current.

613 D. Movement of Lines of Force with Change of Magnetization.—As long as a piece of iron or steel remains unchanged in its magnetization, its tubes of force are to be conceived of as a rigid system rigidly connected with it. When the intensity of magnetization is increased, new tubes are added and the old ones are crushed together. The new tubes are to be regarded as coming into existence at the magnetic axis of the magnet, and pushing the old ones further away from the axis. When the intensity of magnetization falls off, a reverse motion occurs, and the axis absorbs those tubes which lie next it.

Similar remarks apply to changes of strength in a current. The lines of magnetic force due to a current in a wire are circles, and the tubes of force are rings, having the wire for their common axis. When the current receives an increase of strength, the new rings must all be conceived of as starting from the wire, and pushing out the old rings before them, and on the diminution or cessation of the current a reverse movement occurs.

When a current suddenly commences in a wire, or a piece of soft iron is suddenly magnetized, a neighbouring wire is cut through by as many tubes of force, and subjected to the same inductive influence, as if it were suddenly moved up from a great distance into its actual position. The experimental results described in § 609–612 are thus only particular cases of the general principles of § 613 A, B.

613 E. Motion in Uniform Field.—If we define a uniform magnetic field as a field of uniform intensity, it can be shown to follow, as a mathematical consequence, that the equipotential surfaces must be parallel planes, and the lines of force parallel straight lines. The tubes of force will, of course, be of uniform section, and the number of tubes per unit of cross section will be equal to I, the intensity of the field. The electro-motive force generated by the motion of a straight wire of length L in such a field, with a velocity of translation V, being equal to the number of tubes cut through in unit time, will be LVI, if the length of the wire and the direction of motion are perpendicular to each other and to the lines of force. For any other position of the wire, and for any other direction of motion, the number of tubes cut through will evidently be less. If the length of the wire is parallel to the lines of force, no tubes will be cut through, whatever be the direction of motion; and if the direction of motion be parallel to the lines of force, no tubes will be cut through, whatever be the position of the wire. In these two cases, then, there is no generation of electro-motive force tending to produce a current along the wire.

Terrestrial magnetism furnishes us with an example of a uniform field, so long as we confine our attention to a space of moderate dimensions, such as the interior of a room.

613F. Unit of Resistance.—Units of *length*, *mass*, and *time*, having been selected, unit *force* is defined as that which, acting on unit mass for unit time, generates unit velocity.

A magnetic pole of unit strength, or a unit *pole*, is defined as that which attracts or repels an equal pole at unit distance with unit force.

Unit *intensity of field* is defined as the intensity at a place where a unit pole experiences unit force.

A unit *current*, or a current of unit strength, is one which, for each unit of its length, affects a unit pole at unit distance with unit force. In passing through a circular coil of unit radius and length l, the force which it exerts on a unit pole at the centre is l.

Unit *electro-motive force* is the electro-motive force existing in a circuit in which unit current does unit work in each unit of time; and unit *resistance* is the resistance of a circuit in which unit electro-motive force would produce unit current.

The course of the above investigation shows that the units of length, mass, and time are sufficient to determine all the other units mentioned. It can further be shown[1] that the unit of resistance is independent of the unit of mass, and depends only on the units of length and time, being directly as the unit of length, and inversely as the unit of time—a property which is also characteristic of the unit of velocity. Hence a resistance, like a velocity, can be adequately expressed in *metres per second*. The unit of resistance now commonly employed is the *ohm*, which is defined as *ten million metres per second*. The resistance of an ordinary Daniell's cell is about half an ohm. The resistance of a mile of submarine telegraph-cable is from 4 to 12 ohms.

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[1] See appendix at the end of this chapter.

614. Induction by means of Terrestrial Magnetism.—If a wire ring, or any other form of closed circuit, receives a movement of translation in a uniform field, no current is generated, because the same number of force-tubes are cut negatively as positively. Whatever currents are generated by the motion of a closed circuit in the terrestrial magnetic field, must therefore be due solely to rotational movements. Suppose the circuit to consist of a single circle of wire, and let it be initially placed so that its plane is perpendicular to the dipping-needle, and therefore perpendicular to the lines of magnetic force. In this position, the number of force-tubes which it incloses is equal to the product of the inclosed area by the total intensity of terrestrial magnetic force, that is to $\pi r^2 I$, I denoting this intensity, and r the radius of the circle. Now let the ring rotate through 180° about any diameter, so that it comes back into its original place, but facing the opposite way. During this semi-revolution, each half of the ring has cut through all the tubes which passed through the ring, and though in one sense the two halves have been cutting the tubes in opposite directions, the application of the criterion of § 613 B shows that the resulting currents are in the same direction round the circuit. The number of tubes cut through is therefore to be reckoned as $2\pi r^2 I$, and the quotient of this by the time occupied in a semi-revolution is the average electro-motive force (§ 613 E). If the rotation be uniform, the actual electro-motive force is greatest in the middle of the semi-revolution, and is zero at its commencement and termination. During the other half-revolution the circumstances are precisely the same, except that the two halves of the ring have changed places. If we compare the currents in two positions of the ring which differ by 180°, we see that the current round the ring has the same direction in space, but opposite directions as regards the ring itself.

If, instead of a single ring of wire, we have a circular coil consisting of any number of convolutions, with its two ends united, the same principles apply. If there are n convolutions, the electromotive force will be n times greater than with one, but as the resistance is also n times greater the strength of current is the same.

In the apparatus called *Delezenne's Circle*, a coil of wire revolves about a diameter, but the two ends of the coil, instead of being directly united, are so connected with the two ends of the axis of rotation that the circuit is completed through a galvanometer. On rotating the coil rapidly by means of a handle provided for the purpose, a current is indicated by the galvanometer, and this current is found to be strongest (for a given rate of rotation) when the axis is perpendicular to the dipping-needle. If the axis is inclined at an angle θ to the dipping-needle, the current is proportional to $\sin\theta$; and if the axis is parallel to the dipping-needle there is no current at all. For a given position of the axis, the current varies directly as the speed of rotation. When the time of a revolution is only a small fraction of the time in which the needle would oscillate, the variations of electro-motive force, and consequently of current, which take place during a revolution, have not time to manifest themselves, and the deflection of the needle is that due to the average current. It is necessary, however, that a commutator be employed to prevent the reversal of the current at each half-revolution. The proportionality of the current to $\sin\theta$ is easily inferred from the principles of the foregoing sections; for if the plane of a circle, instead of being perpendicular to the lines of force, is inclined to them at an angle θ, the number of force-tubes which it incloses will be not $\pi r^2 I$, but $\pi r^2 I \sin\theta$.

614 A. British Association Experiment.—The experiments upon which the present standards of resistance depend for their authority, were conducted by a committee of the British Association in 1862. A circular coil of wire, with its ends joined, was made to revolve rapidly, at a measured rate, about a vertical axis; and the current induced was measured by the deflection of a magnetized needle suspended, within a glass case, in the centre of the coil. The part of the earth's magnetic force which comes into play in this arrangement, is only the horizontal component, or $I\cos\delta$, δ denoting the dip; and it is worthy of remark that variations in the horizontal intensity do not alter the deflection of the needle, since they affect to the same extent the amount of the induced current, and the terrestrial couple on the needle tending to resist deflection.

All the other elements involved were determined by observation, and hence the value of R in metres per second was calculated. By comparing the resistances of other coils with that of the coil used in this experiment (a comparison easily made by ordinary methods), their values in metres per second were at once determined; and it was easy to construct a resistance-coil of ten million metres per second, or any other desired amount of resistance. Standard resistance-coils are usually made of German silver; this material being selected on account of the smallness of its temperature correction. All metals have their resistances increased by heat, and a standard coil can therefore only be correct at one particular temperature.

615. Induction of a Current on Itself: Extra Current.—If two portions of the same wire are side by side, the sudden commencement or cessation of a current in one, induces a current in the other, just as if they were portions of two unconnected circuits. An action of this kind occurs whenever a current commences or ceases in a coil, each convolution exercising an inductive influence on the rest. This action is called the *induction of a current upon itself*, and the current due to it is called an *extra current*.

The extra current on the commencement of the primary current is inverse, and merely acts as a hindrance to commencement; but the extra current on the stoppage of the primary current is direct, and is often a strongly-marked phenomenon. Hence it is that, with batteries of ordinary power, a spark is obtained on breaking, but not on making connection. The spark is particularly brilliant when a coil of many convolutions is included in the circuit, and especially if this coil incloses a core of soft iron. If an observer holds in his hands two metallic handles permanently connected with the two ends of such a coil, and if the circuit of the battery is alternately made and broken, he will receive a shock from the extra current at each interruption. If the interruptions succeed each other rapidly, the physiological effect may become very intense. Many of the machines employed for medical purposes are constructed on this plan.

Special contrivances are provided for producing a rapid succession of interruptions at regular intervals. They are called *rheotomes* or *contact-breakers*. Sometimes they consist of toothed wheels turned by hand,—sometimes of vibrating armatures moved automatically.

616. Ruhmkorff's Induction-coil.—Induced currents capable of producing very striking effects are furnished by the apparatus first successfully constructed by Ruhmkorff, and hence known as Ruhmkorff's coil.

It contains two coils of wire, one of them forming part of the circuit of a battery, and called the primary coil; while in the other, called the secondary coil, the induced currents are generated. In the axis of the coils is a bundle of stout straight wires of soft iron, with a disc of the same material at each end, to which the wires are united. Around this core is wound the primary coil, consisting of a copper wire about two millimetres in diameter. The ends of this wire are shown at *f* and *f′*. The secondary coil consists of much finer wire (about a quarter of a millimetre in diameter) and of much greater length. In large instruments the primary coil may have a length of 80 metres, and the secondary a length of 150 kilometres (94 miles). Special precautions must be taken to insulate the different convolutions of the secondary coil from one another, and from the primary coil. The two ends of the secondary wire are at the binding-screws A, B, which are supported on glass pillars. It is obvious that if currents are alternately passed and stopped in the primary coil, there will be an alternate generation of currents (or at all events of electro-motive forces) in opposite directions in the secondary coil The action of the core is similar to that of the soft-iron bar in Fig. 545, and its inductive effect is always in the same direction as that of the primary coil, for the primary coil may itself be regarded as a temporary magnet with its poles turned the same way as those of the core.

The successive makes and breaks are effected automatically in various ways. In small instruments the arrangement adopted is usually the same as that of the vibrating alarum described in § 587;

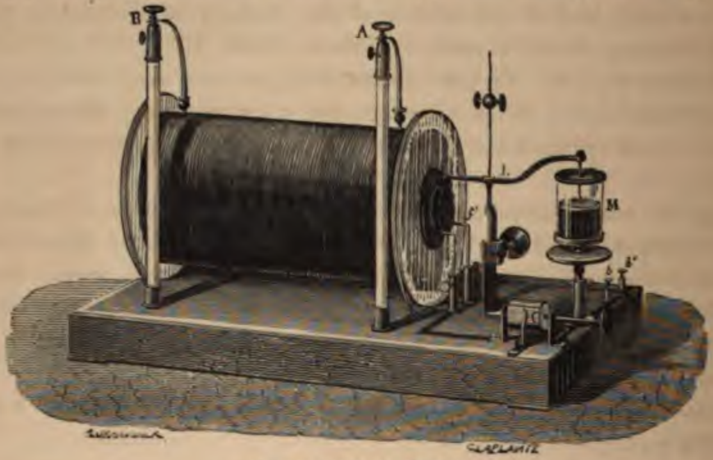

Fig. 547.—Ruhmkorff's Coil.

but for large instruments Foucault's contact-breaker is preferred. It is represented in its place in Fig. 547.

The wires from the battery are attached at *b* and *b′*. The current, entering for example at *b*, passes to the commutator C, and thence, through a brass bar let into the table, to the end *f* of the primary coil. Having traversed this coil, it comes out at *f′*, and is conducted to a vertical pillar, carrying at its upper end a spring, to which the transverse lever L is attached. One end of the lever carries a point which just dips in the mercury of the vessel M, the bottom of which is metallic, and is in communication with *b′*. The other end of the lever carries a small armature of soft iron just above the end of the core.

When the current passes, the core becomes magnetized and attracts this armature, thus lifting the point at the other end of the lever out of the mercury and breaking circuit. The core being thus demagnetized, the elasticity of the spring releases the armature, and the point again dips in the mercury, and completes the circuit. A thin layer of absolute alcohol is usually poured on the surface of the mercury, and serves, by its eminent non-conducting power, to make the interruptions and renewals of the current more sudden.

The *commutator* C is a frequent appendage to electrical apparatus, its office being to stop the current from passing, or to make it pass in either direction at pleasure. As fitted to Ruhmkorff's coil, it has usually the form represented in end view and bird's-eye view in the two parts of Fig. 548. There is a cylinder of insulating material turning by means of metallic axle-ends on insulating supports. One of the axle-ends is connected by means of the screw *g* with the brass plate C on the surface of the cylinder. A similar plate C′ on the opposite side is in like manner permanently connected with the other axle-end by the screw *g′*. These two plates C C′ leave between them a considerable portion of the insulating surface of the cylinder uncovered. In the position represented in Fig. 548, the two binding-screws A A′ are connected respectively with the two axle-ends. If the commutator were turned (by its milled head) through 180°, these connections would be reversed; and

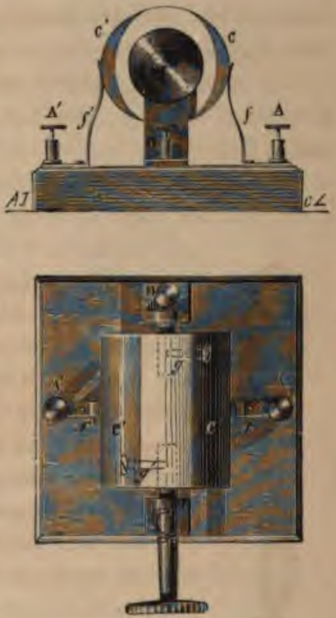

Fig. 548.—Commutator.

if it were turned through 90°, the connections would be interrupted, as the contact-springs *ff′* would bear against the uncovered portions of the insulating cylinder. The milled head is of course insulated from the axle-ends so as to protect the operator.

617. Spark from Induction Coil.—When the ends of the secondary coil are connected, currents traverse it alternately in opposite directions, as the primary circuit is made and broken. These opposite currents convey equal quantities of electricity, and if they are employed for decomposing water in a voltameter, the same proportions of oxygen and hydrogen are collected at both electrodes. If, however, the ends are disconnected, so that only disruptive discharge can occur between them, the inverse current, on account of its lower electro-motive force, is unable to overcome the intervening resistance, and only the direct current passes (that is, the current produced by breaking the primary circuit). The sparks are from an inch to about 18 inches long, according to the size and power of the apparatus, and exhibit effects comparable to those obtained by electrical machines. A Leyden battery may be charged, glass pierced, or combustible bodies inflamed.

The great electro-motive force of the induced current, which enables it to produce these striking effects, depends on the great number of convolutions of the secondary coil, and on the suddenness of the interruptions of the primary current. The quantity of electricity which passes through the secondary coil depends on the product of the number of convolutions by the number of tubes of force which cut through them (§ 613 F), and is the same whether the cessation be sudden or gradual; but the electro-motive force varies inversely as the time occupied.

The discharges from a Ruhmkorff's coil become more violent and detonating if the two electrodes are connected respectively with the two coatings of a Leyden jar or other condenser. An apparatus consisting of numerous sheets of tin-foil separated by oiled silk (alternate sheets of foil being connected) is frequently employed for this purpose, and is placed beneath the instrument so as to be out of sight.

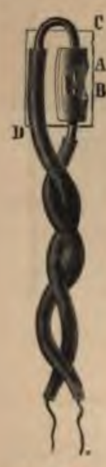

Fig. 549.
Statham's Fuse.

Induction coils are often used for firing mines, by means of Statham's fuse, which is represented in the annexed figure (Fig. 549). Two copper wires covered with gutta-percha have their ends separated by a space of a few millimetres, and inclosed in a little cylinder of gutta-percha containing sulphuret of copper. This, again, is inclosed in a cartridge, C D, which is filled up with gunpowder. The two wires are connected with the two ends of the secondary coil, and when the instrument is set in action, sparks pass between the ends A, B, heating the sulphuret of copper to redness, and exploding the powder.

618. Discharge in Rarefied Gases.—When the ends of the secondary coil are connected with the electrodes of the electric egg (Fig. 550), which has first been exhausted as completely as possible by the air-pump, a luminous sheaf, of purple colour, is seen extending from the positive ball to within a little distance of the negative ball. The latter is surrounded by a bluish glow. The blue and purple lights are separated by a small interval of darkness. If other gases are used instead of air, the tints change, but there is always a decided difference of tint between the positive and negative extremities. By the aid of the commutator it is easy to reverse the current, and thus produce at pleasure an interchange of the appearances presented by the two terminals.

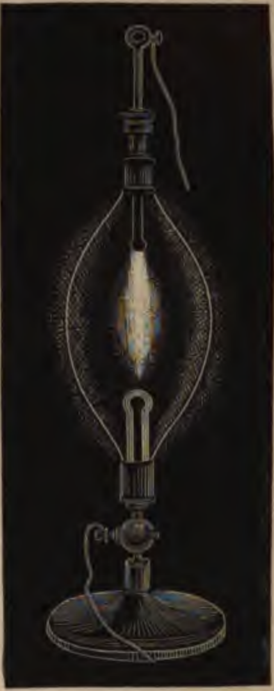
Fig. 550.—Electric Egg.

If, before exhausting, we introduce into the egg a little alcohol, turpentine, or other volatile liquid, the light presents a series of bright bands alternating with dark spaces. Plate II. Fig. 1 represents these stratifications as seen in vapour of alcohol.

The phenomenon of stratification is seen to more advantage in long tubes than in the electric egg; and the presence of alcoholic or other vapour may be dispensed with if the exhaustion be carried sufficiently far, as in the tubes constructed by Geissler of Bonn, which contain various gases very highly rarefied, and have platinum wires sealed into their extremities to serve as electrodes. Four such tubes are represented in Plate II. Certain substances, such as uranium glass, and solution of sulphate of quinine, become luminous in the presence of the electric light, and are called *fluores-*

cent. Such substances are often introduced into Geissler's tubes, for the sake of the brilliant effects which they produce.

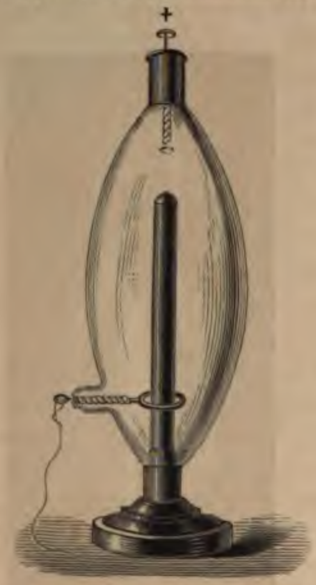

Fig. 551.—Action of Magnets on the Discharge.

619. Action of Magnets on Currents in Rarefied Gases.—The luminous discharges in Geissler's tubes are, like the *voltaic arc,* veritable currents. They are capable of deflecting a magnetized needle, and are themselves acted on by magnets, as in the following experiment. A soft-iron rod (Fig. 551) is fitted in the interior of a glass vessel from which the air can be exhausted, and is coated with an insulating substance to prevent discharge between it and a metallic ring which surrounds it near its lower end. When the terminals of a battery are connected, one with this ring, and the other with the upper end of the apparatus, a luminous sheaf extends from the summit towards the wire ring, and surrounds the soft iron. If, while things are in this condition, we place beneath the apparatus one pole either of a permanent magnet or an electro-magnet, the soft-iron rod is magnetized, and the luminous streaks immediately begin to revolve round it, the direction of rotation being always in accordance with the rule of § 531 B.

620. Magneto-electric Machines.—Faraday's discovery of the induction of currents by magnets, was speedily utilized in the construction of magneto-electric machines, which, without a battery, and with no other stimulus than that afforded by the presence of a permanent magnet, enable the operator, by the expenditure of mechanical work, to obtain powerful electrical effects. The first machine of this kind was constructed in 1833 by Pixii. A magnet A was made to revolve close to a double coil B B′, in which a current was thus generated. The construction was improved by Saxton, and afterwards by Clarke, who made the magnet fixed, and caused the coil, which is much lighter, to rotate in front of it. Clarke's machine is extremely well known, being found in nearly all collections of physical apparatus.

621. Clarke's Machine.—In this machine there is a compound horse-shoe magnet fixed to a vertical support. Close in front of the magnet, near its poles, are two connected coils t, t', each containing a soft-iron core. The two cores are united by a plate of copper on the side next the magnet, and by a plate of soft iron on the remote side. The direction of winding in the two coils is the same as for an ordinary horse-shoe electro-magnet. The coils are mounted on an axis f, which passes through the support of the steel magnet, and carries a pinion. By means of an endless chain passing over this pinion, and over a large wheel to which a handle is attached, the

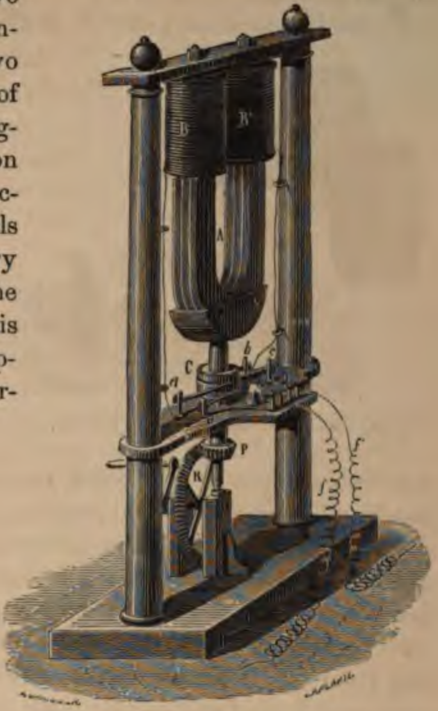

Fig. 552.—Pixii's Machine.

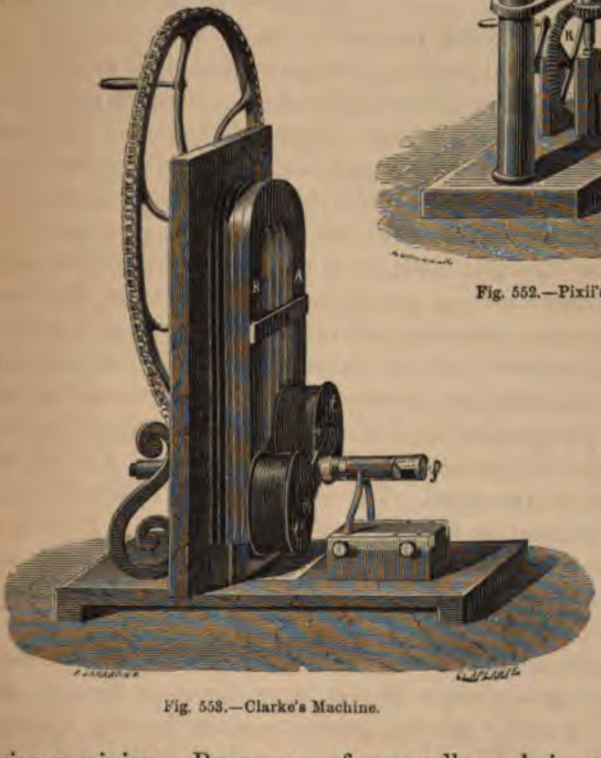

Fig. 553.—Clarke's Machine.

pinion, and with it the coils, can be made to revolve rapidly. The ends of the wire which forms the two coils are connected respectively with the two metallic pieces E, E′ (Fig. 554), which are mounted on the axis, but insulated from it and from each other.

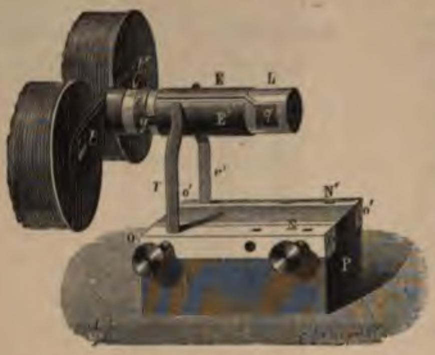

Fig. 554.—Commutator of Clarke's Machine.

Let us now examine the formation of the currents. The two iron cores, with their connecting iron plate, may be regarded as a temporary horseshoe magnet, whose poles are always of opposite name to those of the steel magnet which are respectively nearest to them. The intensity of magnetization is greatest when the soft-iron magnet is horizontal, vanishes when it is vertical, and in passing through the vertical position undergoes reversal. If we call one direction of magnetization positive and the opposite direction negative, the strongest positive magnetization corresponds to one of the two horizontal positions, and the strongest negative to the other, the two positions differing by 180°. While the magnet, then, is revolving from one horizontal position to the other, its magnetization is changing from the strongest positive to the strongest negative, and this change produces a current in one definite direction in the surrounding coil. During the next half-revolution the magnetization is again gradually reversed, and an opposite current is generated in the coil. If we examine the direction of the currents due to the cutting across of the lines of force of the permanent magnet by the convolutions of the coil, we shall find that they concur with those due to the action of the cores. The current in the coils circulates in one direction as long as the electro-magnet is moving from one horizontal position to the other, and changes its direction at the instant when the cores come opposite the poles of the steel magnet.

By the aid of the commutator represented in Fig. 554, the currents may be made to pass always in the same direction through an external circuit. r and r' are two contact-springs bearing against the two metal pieces E, E′, which are the terminals of the coil. At the instant when the current in the coil is reversed, these springs are in contact with intermediate insulating pieces which separate the metallic pieces E, E′. When the current in the coil is in one direction (say from E to E′), *r* is in contact with E, and *r*′ with E′. When the current in the coil is in the opposite direction (E′ to E), *r* is in contact with E′, and *r*′ with E; thus in each case *r* is the positive and *r*′ the negative spring, and the current will be from *r* to *r*′ in an external connecting wire. O O, O′O′, are metallic pieces insulated from each other, and connected with the springs *r r*′ respectively. Binding-screws are provided for attaching wires through which the current is to be passed.

With this machine water can be decomposed, wire heated to redness, or soft iron magnetized; but these effects are usually on a small scale on account of the small dimensions of the machine.

For giving shocks, two wires furnished with metallic handles are attached to the binding-screws, and a third spring is employed which puts the terminals E E′ in direct connection with each other twice in each revolution, by making contact with two plates *q*. When these contacts cease, the current is greatly diminished by having to pass through the body of the person holding the handles, and the extra-current thus induced gives the shock. To obtain the strongest effect, the hands should be moistened with acidulated water before grasping the handles.

622. Magneto-electric Machines for Lighthouses.—Very powerful effects can be obtained from magneto-electric machines of large size driven rapidly. Such machines were first suggested by Professor Nollet of Brussels; and they have been constructed by Holmes of London and the Compagnie l'Alliance of Paris. It is by means of these machines that the electric light is maintained in lighthouses; they have also been employed to some extent in electro-metallurgy. Fig. 555 represents the pattern adopted by the French company. It has eight rows of compound horse-shoe magnets fixed symmetrically round a cast-iron frame. They are so arranged that opposite poles always succeed each other, both in each row and in each circular set. There are seven of these circular sets, with of course six intervening spaces. Six bronze wheels, mounted on one central axis, revolve in these intervals, the axis being driven by steam-power transmitted by a pulley and belt. The speed of rotation is usually about 350 revolutions of the axis per minute. Each of the six bronze wheels carries at its circumference sixteen coils, corresponding to the number of poles in each circular set. The core of each coil is a cleft tube of soft iron, this form having been found peculiarly favourable to rapid demagnetization.

Each core has its magnetism reversed sixteen times in each revolu-

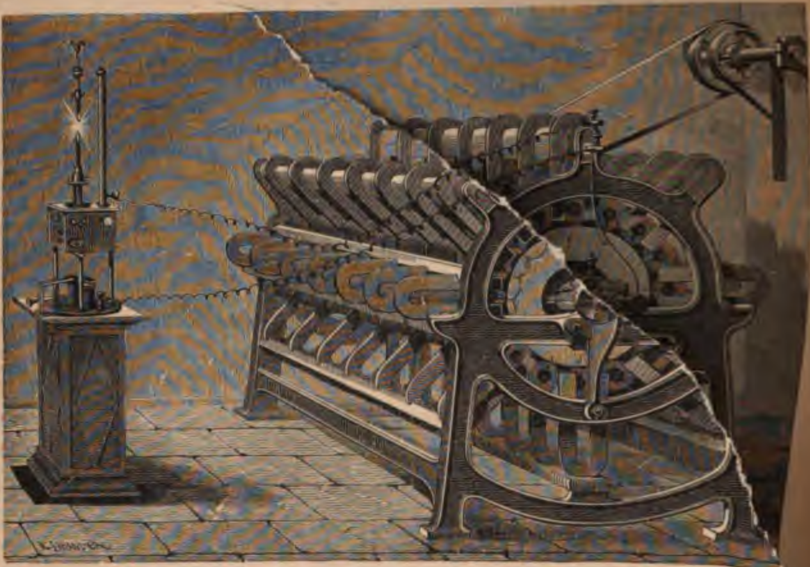

Fig. 555.—Lighthouse Machine.

tion, by the influence of the sixteen successive pairs of poles betwee which it passes, and the same number of currents in alternatel opposite directions are generated in the coils. The coils can be connected in different ways, according as great electro-motive force o small resistance is required. The positive ends are connected with the axis of the machine, which thus serves as the positive electrode, and a concentric cylinder, well insulated from it, is employed as th negative electrode.

When the machine is employed for the production of the electr light, the currents may be transmitted to the carbon points in alte nate directions, as they are produced. For electro-metallurgi purposes they are brought into one constant direction by a co mutator, as in Clarke's machine above described. The driving-po required for lighthouse purposes is about three horse-power.

623. Siemens' Armature.—An important improvement in Clark machine was introduced by Siemens of Berlin in 1854. It consi in the adoption of a peculiar form of electro-magnet, which is rep sented in Fig. 556. The iron portion is a cylinder with a very deep and wide groove cut along a pair of opposite sides, and continued round the ends. The coil is wound in this groove like thread upon a shuttle. Regarded as an electro-magnet, the poles are not the ends of the cylinder, but are the two cylindrical faces which have not been cut away. In Fig. 557, *a b* is a section of the armature with the coil wound upon it. ABMN is a socket within which the armature revolves, the portions AB being of iron, and MN of brass.

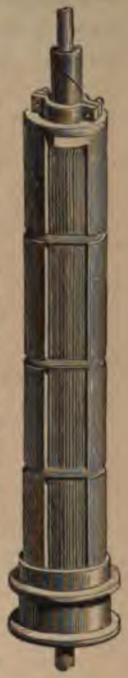

Fig. 556. Siemens' Armature.

The advantage of Siemens' armature is that, on account of the small space required for its rotation, it can be kept in a region of very intense magnetic force by the use of comparatively small magnets. Its form is also eminently favourable to rapid rotation. It is placed between the opposite poles of a row of horse-shoe magnets which bestride it along the whole of its length, as shown at the top of Fig. 559, and is rotated by means of a driving-band passing over the pulley shown at the lower end of Fig. 556.

The polarity of the electro-magnet is reversed at each half-revolution as in Clarke's arrangement, and the alternately opposite currents generated are reduced to a common direction by a commutator nearly identical with Clarke's, and represented in Figs. 556, 558. Siemens' machines are much more powerful than Clarke's when of the same size.

624. Accumulation by Successive Action: Wilde's Machine.—By employing the current from a Siemens' machine to magnetize soft

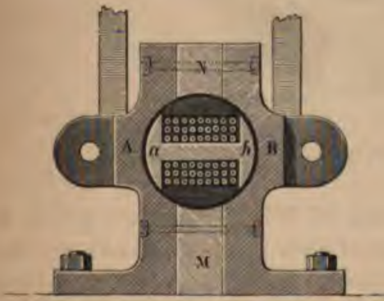

Fig. 557.—Section of Siemens' Armature.

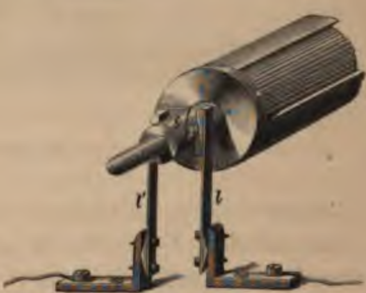

Fig. 558.—Commutator.

iron, we can obtain an electro-magnet of much greater power than the steel magnets from whose induction the current was derived. By causing a second coil to rotate between the poles of this electro-magnet, we can obtain a current of much greater power than the primary current. This is the principle of Wilde's machine, which is represented in Fig. 559. It consists of two Siemens' machines, one above the other. The upper machine derives its inductive action from a row of steel magnets M, whose poles rest on the soft-iron masses m, n, forming the sides of the socket within which a Siemens' armature r rotates. The currents generated in the coil, after being

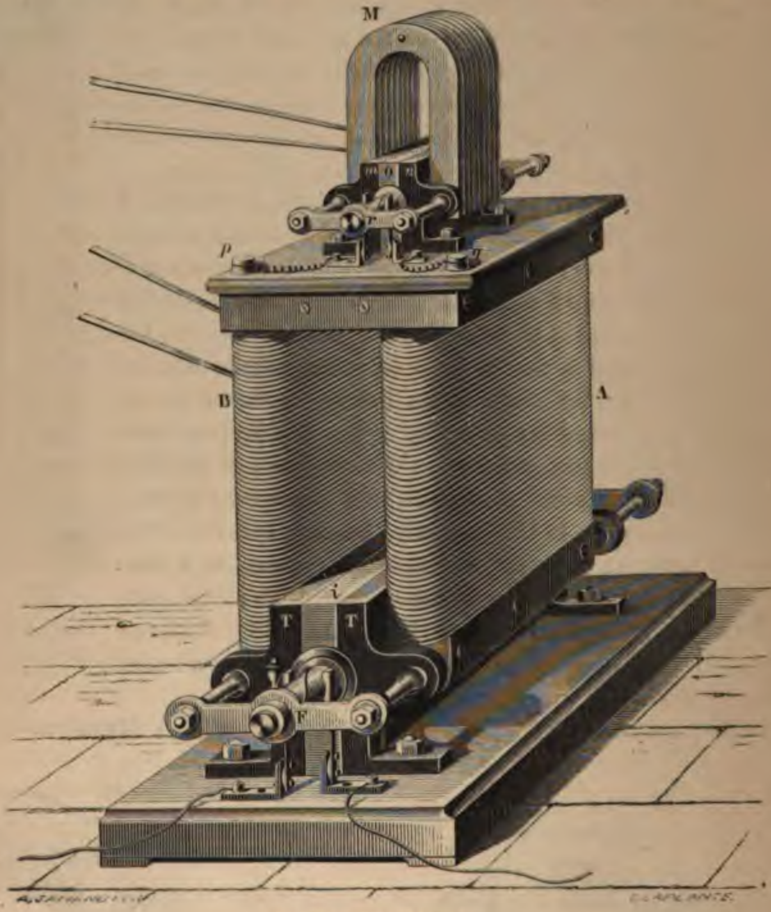

Fig. 559.—Wilde's Machine.

reduced to a uniform direction by a commutator, flow to the binding-screws *p*, *q*. These are the terminals of the coil of the large electro-magnet A B, through which accordingly the current circulates. The core of this electro-magnet consists of two large plates of iron, connected above by another iron plate, which supports the primary machine. Its lower extremities rest, like those of the primary magnets, on two iron masses T, T, separated by a mass of brass *i*; and a second Siemens' armature F, of large size, revolving within this system, furnishes the currents which are utilized externally.

Wilde's machine produces calorific and luminous effects of remarkable intensity; but the speed of rotation required is very great, being sometimes 1500 revolutions a minute for the large, and 2000 for the small armature. This great speed involves serious inconveniences; and the machine does not appear to have been used for lighthouses, or other practical purposes.

Wilde's principle can be carried further. The current of the second armature can be employed to animate a second electro-magnet of greater power than the first, with a third Siemens' armature revolving between its poles. This has actually been done by Wilde. By means of the current from this triple machine, driven by 15 horse-power, the electric light was maintained between two carbons as thick as a man's finger, and a bar of platinum 2 feet long and a quarter of an inch in diameter was quickly melted.

This system of accumulation could probably be carried several steps further, but always with the expenditure of a proportionately large amount of energy in driving it. In no magneto-electric machine can the electrical energy obtained exceed the mechanical energy expended in producing it.

625. Accumulation by Mutual Action: Siemens' and Wheatstone's Machine.—Siemens and Wheatstone nearly simultaneously proposed the construction of a magneto-electric machine in which the induced currents are made to circulate round the soft-iron magnet which produced them. Iron has usually some traces of permanent magnetism, especially if it has once been magnetized. This magnetism serves to induce very feeble currents in a revolving armature. These currents are sent round the iron magnet, thus increasing its magnetization. This again produces a proportionate increase in the induced currents; and thus, by a successive alternation of mutual actions, very intense magnetization and very powerful currents are speedily obtained. In the machine as exhibited by Siemens in 1867, the current was diverted into an external circuit, at regular intervals, by an automatic arrangement.

626. Ladd's Machine.—Ladd in 1867 constructed a machine based on the principle of mutual action just described; but, instead of utilizing the current by occasional interruptions, he employed a second revolving armature whose coil was in permanent connection with the external circuit.

B, B′ (Fig. 560) are two plates of iron surrounded by coils which are connected at the right-hand end so as to form but one circuit. The other ends are attached to two binding-screws connected with the ends of the coil of a Siemens' armature a'. The direction of winding of the two large coils BB′ is the same as for a horse-shoe magnet, so that the two poles at either end are of opposite sign. The ends of the cores are let into masses of soft iron M M, N N, between which two armatures a a' rotate. The coil of the armature a is connected with the external circuit containing, for example, two carbon points for exhibiting the electric light.

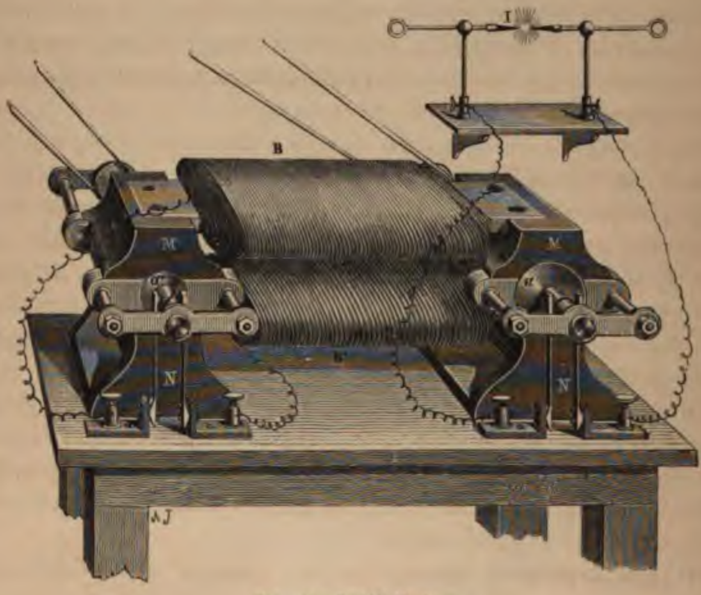

Fig. 560.—Ladd's Machine.

On the principle of mutual action, the electro-magnets B, B′, which we may suppose to have at first only a trace of magnetism, are soon raised to very intense magnetization by the rapid rotation of the armature *a'*, and as long as the rotation continues, the magnetization is maintained. The rapid rotation of the other armature *a* between the poles thus strongly excited, produces a very powerful current which can be utilized externally.

Ruhmkorff has modified the arrangement by using a single rotating armature with two coils wound upon it, one of them being connected with the electro-magnet, and the other with the external circuit.

The efficiency of machines of this description, regarded as means for the transformation of mechanical into electrical energy, is undoubtedly very considerable; nevertheless it is not perfect, a large amount of energy being wasted in generating heat. On account of the high velocity necessary for efficient working, and the small size of the apparatus in comparison with the currents obtained, the elevation of temperature is often so great as to prove a source of much annoyance.

626 A. Wheatstone's Telegraphic Currents.—In Wheatstone's Universal Telegraph, which has been partially described in a previous chapter, the magneto-electric currents which give the signals are produced by causing a small flat bar of soft iron to rotate rapidly before the poles of a steel horse-shoe magnet, which has two connected coils of wire wound upon it in the same manner as upon electro-magnets. It is in these coils that the currents are generated, the iron bar being a temporary magnet, and thus influencing the coils nearly in the same manner as if it were a permanent magnet. A current is induced in one direction as it approaches the poles, and in the opposite direction as it recedes from them, so that altogether four currents are generated in each complete revolution. On account of the lightness of the bar, it can be rotated with great rapidity.

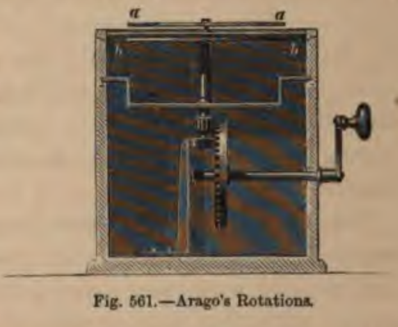

Fig. 561.—Arago's Rotations.

627. Arago's Rotations.—Faraday successfully applied his discovery of magneto-electric induction to account for a phenomenon first observed by Arago in 1824, and subsequently investigated by Babbage and Sir John Herschel. A horizontal disc of copper *b b*, placed in the interior of a box, is set in rapid rotation by turning a handle. Just over the copper disc, but above the thin plate which forms the top of the box, a magnetized needle *aa* is balanced horizontally. When the disc is made to rotate, the needle is observed to deviate from the meridian in the direction of the rotation. When the speed of rotation exceeds a certain limit, the needle is not only deflected, but carried round in continuous rotation in the same direction as the disc.

The explanation is to be found in the currents which are induced in the disc by its motion in the vicinity of the magnetized needle. The forces between these currents and the needle are (by Lenz's law) such as to urge the disc backwards; and, from the universal relation which subsists between action and reaction, they must be such as to urge the needle forwards; hence the motion. The direction of the induced current at any instant is in fact along that diameter of the disc which is directly under the needle, the circuit being completed through the lateral portions of the disc; and it is evident that a current thus flowing parallel to the needle underneath it tends to produce deflection. If the continuity of the disc is interrupted by radial slits, the observed effect is considerably weakened inasmuch as the return circuit is broken. Faraday succeeded in directly demonstrating the existence of currents in a disc rotating near a fixed magnet, by exploring its surface with the amalgamated ends of two wires connected with a galvanometer.

The experiment performed by Arago may be reversed by setting the magnet in rotation, and observing the effect produced on the disc. The latter, if delicately suspended, will be found to rotate in the same direction as the magnet. This experiment was first performed by Babbage and Herschel. Its explanation is identical with that just given. In both cases the induced rotation must be slower than that of the body turned by hand, as the existence of the induced currents depends upon the motion of the one body relative to the other.

When an iron disc is used instead of a copper one, magnetism is induced in the portions which pass under the poles of the magnet; and as this requires a sensible time for its disappearance, there is always attraction between the poles of the needle and the portions of the disc which have just moved past. The needle is thus drawn forwards by magnetic attraction, and the observed effect is similar to that obtained with the copper disc, though the cause[1] is altogether different.

627A. Copper Dampers.—Precisely similar to the above is the explanation of the utility of a copper disc in checking the vibrations of a magnetized needle under which it is fixed. As the needle swings to either side, its motion induces currents in the copper which urge the needle in the opposite direction to that in which it is moving. When it rests for an instant at the extremity of its swing, the currents cease; and as soon as it begins to return, the currents again resist its motion. A copper plate thus used is called a *damper*, and the vibrations thus resisted and destroyed are said to be *damped*. The name is applied to any other means for gradually destroying vibrations, and is probably based on the analogy between this action and the steadying action of a liquid upon a suspended body immersed in it.

The resistance which induced currents oppose to the motion producing them is well illustrated by Faraday's experiment of the *copper cube*. A cube of copper is suspended by a thread, and set spinning by twisting the thread and then allowing it to untwist. If, while spinning, it is held between the poles of a powerful magnet, like that represented in Fig. 432, it is instantly brought to rest. If the poles are brought very near together, so as to heighten the intensity of the field, and a thin sheet of copper is inserted between them and moved rapidly in its own plane, the operator feels its motion resisted by some invisible influence. The sensation has been compared to that of cutting cheese. Foucault's apparatus for the heating of a copper disc by rotating it between the poles of a magnet (§ 356), is another illustration of the same principle. In all cases where induced currents are generated, and are not called upon to perform external work, they yield their full equivalent of heat.

The advantage of employing copper in experiments of this kind arises from its superior conductivity, to which the induced currents are proportional.

628. Electro-medical Machines.—The application of electricity is often resorted to for certain nervous affections and local paralyses. Many different forms of apparatus are employed for this purpose.

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[1] That is to say, the *main cause;* for there must be induced currents in the iron as well as in the copper, though inferior in strength, on account of the inferior conductivity of the former metal.

One of the most convenient is represented in Fig. 562. Two small coils connected with each other, and furnished with a vibrating contact-breaker, are traversed by the current from a miniature battery. The coils are surrounded by hollow cylinders of copper or brass, in which induced currents are generated as often as the current in the coils is established or interrupted. This action diminishes the energy of the extra-currents on which the shock depends, and the operator can accordingly regulate its strength at pleasure by sliding the cylinders on or off.

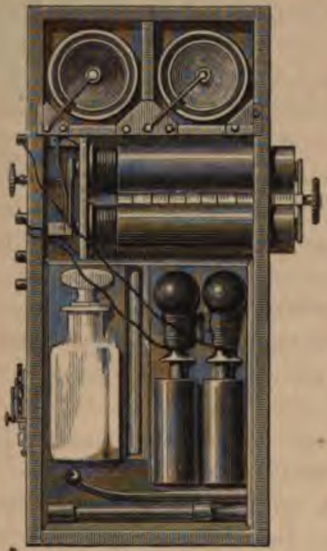

Fig. 562.—Electro-medical Machine.

628A. Caution regarding Lines of Force.—After the very extensive use which has been made in this volume of lines and tubes of force, we think it right to caution the reader against supposing that these conceptions depend upon any doubtful hypothesis. They merely serve, like meridians and parallels of latitude, to map out space in a mode convenient for the statement of physical laws.

APPENDIX.

ON ELECTRICAL AND MAGNETIC UNITS.

(1). The numerical value of a concrete quantity is its ratio to a particular unit of the same kind; the selection of this unit being always more or less arbitrary.

(2). One kind of quantity may, however, be so related to two or more others, as to admit of being specified in terms of units of these other kinds. For example, of the three kinds of quantity, called distance (or length), time, and velocity, any one is capable of being expressed in terms of the other two. Velocity can be specified (as regards amount) by stating the distance passed over in a specified time. Distance can be specified by stating the velocity required for describing it in a specified time, and time can be specified by stating the distance described with a specified velocity.

Force, distance, and work are in like manner three kinds of quantity, of which any two are just sufficient to specify the third.

(3). Calculation is greatly facilitated by employing as few original or underived units as possible. These should be of kinds admitting of easy and accurate comparison; and all other units should be derived from them by the simplest modes of derivation which are available.

(4). Velocity is proportional directly to distance described, and inversely to the time of its description; and is independent of all other elements. This is expressed, by saying that *the dimensions of velocity* are $\frac{\text{distance}}{\text{time}}$ or $\frac{\text{length}}{\text{time}}$.

Again, if we define the unit of velocity to be that with which unit distance would be described in unit time, the real magnitude of the unit of velocity will depend upon the units of length and time selected, being proportional directly to the real magnitude of the former, and inversely to the real magnitude of the latter. This is expressed by saying that *the dimensions of the unit of velocity* are $\frac{\text{length}}{\text{time}}$. Both forms of expression are convenient; and the ideas which they are intended to express are logically equivalent.

(5). All electrical and magnetic units can be derived from units of length, mass, and time. We shall denote length by l, mass by m, and time by t.

(6). The unit of *velocity* is the velocity with which unit length is described in unit time. Its dimensions are $\frac{l}{t}$.

(7). The unit of *acceleration* is the acceleration which gives unit increase of velocity in unit time. Its dimensions are $\frac{\text{velocity}}{\text{time}}$ or $\frac{l}{t^2}$.

(8). The unit *force* is that which acting on unit mass produces unit acceleration. Its dimensions are mass × acceleration, or $\frac{m\,l}{t^2}$.

(9). The unit of *work* is the work done by unit force working through unit length. Its dimensions are force × length, or $\frac{m\,l^2}{t^2}$.

(10). The unit of *kinetic energy* is the kinetic energy of *two* units of mass moving with unit velocity (according to the formula $\frac{1}{2}\,m\,v^2$). Its dimensions are mass × (velocity)^2, or $\frac{m\,l^2}{t^2}$, and are the same as the dimensions of work. It might appear simpler to make it the energy of *one* unit of mass moving with unit velocity; but if this change were made, it would be necessary either to halve the unit of work, or else to make kinetic energy double of the work which produced it. Either of these alternatives would involve greater inconvenience and complexity than the selection made above.

UNITS OF STATICAL ELECTRICITY.

(11). Let q denote *quantity* of electricity measured statically, so that the mutual repulsion of two equal quantities q at distance l, is $\frac{q^2}{l^2}$. This being equal to a force, the dimensions of q^2 must be (length)^2 × force, or $\frac{m\,l^3}{t^2}$, and the dimensions of q must be $\frac{m^{\frac{1}{2}}\,l^{\frac{3}{2}}}{t}$.

(12). Let V denote *difference of potential*. Then the work required to raise a quantity q through a difference of potential V, is $q\,\mathrm{V}$. The dimensions of V are therefore $\frac{\text{work}}{q}$, or $\frac{m\,l^2}{t^2}\,\frac{t}{m^{\frac{1}{2}}\,l^{\frac{3}{2}}}$, or

$\frac{m^{\frac{1}{2}} l^{\frac{1}{2}}}{t}$. The dimensions of potential are of course the same as those of difference of potential.

(13). The *capacity* of a conductor is the quotient of the quantity of electricity with which it is charged, by the potential which this charge produces in the conductor. The dimensions of capacity are therefore $\frac{m^{\frac{1}{2}} l^{\frac{3}{2}}}{t} \cdot \frac{t}{m^{\frac{1}{2}} l^{\frac{1}{2}}}$, or simply l. In fact, as we have seen (§ 445 M), the capacity of a spherical conductor is equal to its radius.

MAGNETIC AND ELECTRO-MAGNETIC UNITS.

(14). Let P denote the numerical value of a *pole* (or the strength of a pole). Then, since two equal poles P at distance l repel each other with the force $\frac{P^2}{l^2}$, which must be of the dimensions $\frac{ml}{t^2}$, the dimensions of P are $\frac{m^{\frac{1}{2}} l^{\frac{3}{2}}}{t}$.

(15). Let I denote the *intensity of* a magnetic *field*. Then, a pole P in this field is acted on with a force P I. This must be of the dimensions $\frac{ml}{t^2}$. Hence, the dimensions of I are $\frac{ml}{t^2} \cdot \frac{t}{m^{\frac{1}{2}} l^{\frac{3}{2}}}$, or $\frac{m^{\frac{1}{2}}}{l^{\frac{1}{2}} t}$.

(16). Let M denote the *moment* of a magnet. Since it is the product of the strength of a pole by the distance between two poles, its dimensions are $\frac{m^{\frac{1}{2}} l^{\frac{5}{2}}}{t}$.

(17). Intensity of *magnetization* is the quotient of moment by volume. Its dimensions are therefore $\frac{M}{l^3}$ or $\frac{m^{\frac{1}{2}}}{l^{\frac{1}{2}} t}$. These are the same as the dimensions of intensity of field.

(18). When a magnetic substance is placed in a magnetic field, it is magnetized by induction; and each substance has its own specific *co-efficient of magnetic induction* (constant, or nearly so, when the field is not excessively intense), which expresses the ratio of the intensity of the induced magnetization to the intensity of the field. For diamagnetic substances, this co-efficient is negative, that is to say, the induced polarity is reversed, end for end, as compared with that of a paramagnetic substance placed in the same field.

(19). The work required to move a pole P from one point to another, is the product of P by the difference of the magnetic potentials of the two points. Hence, the dimensions of *magnetic potential* are $\frac{m l^2}{t^2} \frac{t}{m^{\frac{1}{2}} l^{\frac{3}{2}}}$ or $\frac{m^{\frac{1}{2}} l^{\frac{1}{2}}}{t}$.

(20). A *current* C flowing along a circular arc, produces at the centre of the circle an intensity of field equal to C multiplied by length of arc divided by square of radius. Hence, C divided by a length is equal to a field-intensity, the dimensions of which are $\frac{m^{\frac{1}{2}}}{l^{\frac{1}{2}} t}$, and the dimensions of C are $\frac{m^{\frac{1}{2}} l^{\frac{1}{2}}}{t}$.

(21). The *quantity* Q of electricity conveyed by a current is the product of the current by the time that it lasts. Its dimensions are therefore $m^{\frac{1}{2}} l^{\frac{1}{2}}$.

(22). The work done in urging a quantity Q by an electro-motive force E is E Q, hence the dimensions of *electro-motive force* are $\frac{m l^2}{t^2} \frac{1}{m^{\frac{1}{2}} l^{\frac{1}{2}}}$ or $\frac{m^{\frac{1}{2}} l^{\frac{3}{2}}}{t^2}$; and as electro-motive force is difference of potential, these are also the dimensions of *potential.*

(23). The *capacity* of a conductor is the quotient of quantity of electricity by potential; its dimensions are therefore $\frac{t^2}{l}$.

(24). The *resistance* R of a circuit is, by Ohm's law, equal to $\frac{E}{C}$. Its dimensions are therefore $\frac{m^{\frac{1}{2}} l^{\frac{3}{2}}}{t^2} \frac{t}{m^{\frac{1}{2}} l^{\frac{1}{2}}}$ or $\frac{l}{t}$, and are the same as the dimensions of velocity.

(25). On comparing the dimensions of the same element as measured according to the two systems, it will be observed that they are not identical. The dimensions of quantity of electricity, for example, in the first system, are to its dimensions in the second, as l to t; and the dimensions of capacity are as l^2 to t^2. Accordingly, the ratio of the electro-static to the electro-magnetic unit of quantity is equal to a length divided by a time; that is to say, is equal to a velocity. From experiments in which the same quantity of electricity was measured both statically and magnetically, it appears that this ratio is in fact identical with the velocity of light. Professor Clerk Maxwell maintains that light, electricity, and magnetism are all affections of one and the same medium; that light is an electro-magnetic phenomenon, and that its laws can be deduced from those of electricity and magnetism.

Notwithstanding this difference of dimensions, two quantities of electricity which are equal when compared statically, are also equal when compared magnetically; or if one be double of the other when compared statically, it will also be double of the other when compared magnetically.

(26). An illustration from a somewhat more familiar department may assist the reader in convincing himself that it is possible for one and the same kind of quantity to have different dimensions according to the line of derivation employed. It is well known that uniform spheres attract each other with a force which is directly as the product of their masses, and inversely as the square of the distance between their centres. If this law were made to furnish the unit of force, the dimensions of force would be $\frac{m^2}{l^2}$, instead of $\frac{ml}{t^2}$, as previously found. The ambiguity depends partly on the fact that l in the one formula denotes distance between attracting centres, and in the other distance moved over. It is only when the mode of derivation is distinctly specified, or is too obvious to need specification, that the dimensions of a quantity admit of being determinately stated. As the definition of a derived unit necessarily involves a specification of the mode of its derivation, there is some advantage in speaking of the *dimensions of a unit,* rather than of the dimensions of the quantity which the unit serves to measure.

(27). Derived units are often called *absolute* units; but it seems an abuse of language to define a unit by its *relation* to other arbitrary units, and then call it *absolute.*

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